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The ToolBus: Introducing hierarchy, abstraction, namespaces and relays

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Abstract

Software systems become larger, more complex and often consist of distributed, heterogeneous parts. A coordination architecture can be used to facilitate the communication between the parts, to control the coordination, to abstract away low level details and to allow for structuring of the system. In this thesis the focus is on the abstraction mechanisms and layered structures of coordination architectures. In particular, it discusses the design and implementation of hierarchical abstraction mechanisms in the ToolBus coordination architecture, which can be seen as a first step towards dependable ToolBus systems. Specifically, a hierarchical process structure is introduced along with a communication restriction that enforces abstraction. This restriction has some disadvantages, mainly in the form of chaining, which will be solved by introducing relays. Furthermore, namespaces are introduced as a solution to name clashes of messages and they provide additional (optional) abstraction as well. Finally, a validation is performed on some examples and the implementation details as well as future work are discussed.

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Contents

1 Introduction

In the development of large software systems, there is often much competition from companies that develop similar software. Due to this competition, new software must be developed in a short amount of time, making it impossible to create it entirely from scratch. The well-known solution to this problem is to reuse existing software parts [18] (often called *components*). Also, existing legacy software systems become more and more complex over time [22], mainly because new features are constantly added. Often ad-hoc solutions are used to add the new features, without regard for the architecture of the entire system, which makes such systems harder and harder to maintain. It is good practice to decompose such systems into parts that have clearly defined and coherent functionality [34]. So, both in the development of new software systems as well as in the decomposition of legacy systems, we end up with a system consisting of components.

Individual parts of a system do not generally run in complete isolation; communication between the parts is needed. Therefore, the parts that together form the system need to be integrated to compose the actual system. This raises the question of how to perform this integration and how to describe and analyze the communication between those parts. Today, in many systems, communication may also span multiple machines within a network. Combined with the fact that when systems get larger, the communication usually increases, it makes those questions even harder to answer.

This master's thesis is concerned with *coordination architectures* or *coordination frameworks*, which allow for the coordination of separate activities within a system. They form a solution to the problem described earlier: the integration of and communication between software components. In particular we are interested in the abstraction mechanisms and layered structures of coordination architectures. The largest part of this thesis will be about the design and implementation of hierarchical abstraction mechanisms in a coordination architecture called the ToolBus.

Philips is a company that among other things builds consumer electronics and medical systems, which contain embedded software. They use third party software components and are therefore confronted with the problem of integrating the components with the other software in their systems. Dependability has always been an important issue in the design of embedded software systems. Recently, Philips is focusing some of its research on fault tolerance and self-healing (both in hardware [29] and software [35, 16]), that can be used to increase dependability, especially when integrating third party software. Philips is interested to see if systems running in the ToolBus can be made dependable and this project is a first step in that direction.

The outline of this thesis is as follows. In Section 2 coordination architectures will be introduced and their properties will be discussed. Then one particular coordination architecture, called the ToolBus, will be introduced in Section 3. This is followed by a discussion of literature on coordination architectures (Section 4). Section 5 discusses some of the problems related to the ToolBus (most

notably the lack of structure) as well as the requirements on a solution to the structure-related problems. In Section 6 the proposed solution will be described in detail, including the motivation for choosing this particular solution. This is followed by Section 7, which discusses the relation between the solution and the requirements. Then, in Section 8, a validation of the solution will be performed by investigating the benefit of the changes to some examples. Section 9 deals with all implementation aspects and in Section 10 the conclusions of the entire project are drawn. Finally, Section 11 contains some possibilities for future research.

2 Coordination architectures

The previous section introduced coordination architectures as a solution to the problem of integrating software components and describing and analyzing the communication between them. In this section, a more extended introduction to coordination architectures (and their properties) will be given.

Well-structured systems usually consist of several (cohesive) *parts*. In the early days of software systems, parts were just subroutines in programming languages. Later on, parallel systems allowed for the parallel execution of parts (usually called *tasks*). With the introduction of object models and class hierarchies the focus of parts shifted from subroutines to classes and (cohesive) collections of classes. Nowadays, parts are generally referred to as *components*. However, the term component is used both to refer to a collection of classes as well as to refer to a part of a system in general. Even more recent as components is the notion of open systems [23], in which parts of the system (called *agents*) may dynamically join (and later leave) the system.

Coordination architectures go beyond anything that existed previously; they go beyond parallel systems, beyond object models and class hierarchies and beyond open systems. There are a lot of definitions of what exactly a coordination architecture is. Some of these definitions include "the glue that binds separate activities into an ensemble" [17], "a means of integrating a number of possibly heterogeneous components together, by interfacing with each component in such a way that the collective set forms a single application that can execute on and take advantage of parallel and distributed systems" [32], "meant to close the conceptual gap between the cooperation model of an application and the lower-level communication model used in its implementation" [3] and "provides a framework in which the interaction of active and independent entities called agents can be expressed" [13].

The common factor is that coordination architectures can be used to *coordinate* the interactions between the different parts of an application, thereby supporting (or facilitating) the (high-level) *integration* of software systems. However, the way in which the coordination of the communication between the parts of a system is achieved, is one of the biggest differences between the existing coordination architectures.

The impact of coordination architectures on software development is significant, as "coordination is relevant in design, development, debugging, maintenance, and reuse of all concurrent systems" [3]. Also, the issues in coordination are not just computer science related; coordination is an interdisciplinary issue and includes issues from "organization theory, economics, and biology" [30].

2.1 Properties

Since there are a lot of different definitions of coordination architectures, it is extremely difficult (if not impossible) to give a list of properties that all coordination architectures must satisfy. It is however possible to give a list of

properties that are often associated with coordination architectures and that are satisfied by a lot of them. What follows is a discussion of these properties (or features), including why they are important:

Integration Providing a means to integrate the different parts of a system, by facilitating the communication between those parts. This is the essence of a coordination architecture. However, the way that the integration is achieved is one of the biggest differences between the existing coordination architectures. Also, when the parts of the system are integrated, there is still a difference in how the coordination architecture determines which parts will communicate and which restrictions are imposed on that communication.

Abstraction of computation Enforcing a strict separation of computation (in the different parts of the system) and communication (at a higher level), allowing for the computation parts to be abstracted away. This should decrease the number of dependencies between the different parts of the system (decreased coupling). Also, the computation parts of the system are often not aware of whom they communicate with or how the system is composed. The communication parts connect to the system via some interface and that is all they need to know. This is one the most important properties of coordination architectures.

Heterogeneity Allowing the integration of software components written in different programming languages and running on any computer platform. This allows for legacy systems to be integrated into a system together with newer systems. Also, it allows one to write parts of the system in the language that is best suited for that particular part and it makes systems highly portable. The downside is that conversions are usually needed to make sure the components written in different languages can actually communicate and cooperate, giving rise to decreased performance.

Distributivity Allowing the integration of software components running on different physical machines, for example within a Local Area Network (LAN). This way, the application can be distributed over several machines, thereby increasing the available resources, such as processing power and memory. However, in order for components running on different machines to communicate, network communication is needed. Compared to components running on a single machine, this results in a performance penalty, which may be considerable!

Abstraction of communication Hiding the (low-level) details of the communication, such that programmers need not be concerned with them. The different parts of the system simply interface with the coordination system. They don't have to concern themselves with details of the communication, like where the receiver is located and what communication protocols or media are used. All coordination architectures hide some communication details, but there are differences. Using more 'higher level' communication concepts gives you less control over the details of the communication, thereby possibly decreasing the performance.

Structure/Hierarchy/Abstraction of composition Stimulating the introduction of structure in the system, by grouping parts of the system together into what we will call *components* or *subsystems*. It is then possible to structure the system even further, by introducing a hierarchy (on components) into the system architecture. Finally we can hide the internal details of the components, to obtain an abstraction on the composition of the system (internal details are encapsulated). Introducing structure has several advantages, which include easier maintenance, improved scalability, decreased coupling and stimulation of reuse.

Dynamic Architecture Providing the means for the architecture to change during execution, allowing parts to be added to or removed from the system (at runtime). This way maintenance can be performed on the system while it is running; it is not necessary for the system to go off-line to update it. The downside is that extra administration is needed, as well as mechanisms to facilitate the dynamic restructuring. These mechanisms require resources as well.

Supporting distributivity has clear advantages, but there is a performance penalty. This is true for many features of coordination architectures. It depends on the requirements for a coordination architecture, whether or not it should support certain features. The key here is to *balance* a rich feature set with issues like performance.

2.2 Differences

We have now seen the properties that (most) coordination architectures satisfy. Existing coordination architectures differ from one another by the amount of properties they satisfy, the extent to which they satisfy them and by how they are satisfied. However, besides those properties, there are several other areas in which they can differ:

Formal foundation Some coordination architectures have a formal foundation, including formal semantics. This allows for formal reasoning and analysis of the communication.

Data- vs. control-driven Some coordination architectures are data-driven and others are control-driven [32]. Data-driven coordination architectures evolve around what happens to the data. They usually have some sort of database that contains a large collection of data, which is shared among the parts of the system. Control-driven coordination architectures evolve around the flow of control.

Endogenous vs. Exogenous Closely related to 'data- vs. control-driven' is endogenous vs. exogenous coordination [32]. Endogenous coordination is coordination from 'within'; coordination is mixed in the computation. Exogenous coordination is coordination from 'without'; coordination is not contained inside the module itself.

Application domain Some coordination architectures are designed for a specific application domain, while others are more general and can be used in many application domains.

Implementation status Some coordination architectures are not yet implemented, while some have existed for years and are widely used in practice. Others are no longer under development.

(A)synchronous communication There are coordination architectures that only support synchronous communication, those that only support asynchronous communication and those that support both. Also, some systems support point-to-point connections; some only support (selective) broadcasting. Other systems even support both. Combining these two characteristics results in four different forms of communication: synchronous point-to-point, asynchronous point-to-point, synchronous (selective) broadcast and asynchronous (selective) broadcast.

Data format used Data plays a role in every coordination architecture; it may be more important in data-driven architectures than it is in control-driven ones, but it always plays a role. Data must be represented in some form. Different coordination architectures use different formats to represent data.

Execution Some coordination architectures require compilation of source files before execution, while others interpret source scripts at runtime. Applications that communicate via the coordination architecture may need extra code to be compiled with it to be able to communicate with the rest of the system. Also, conversions between the data formats used by the application and the data formats used in the coordination architecture may be needed.

Language used The languages that coordination architectures use to describe the communications within a system differ. Some use existing languages, while others invent new ones.

Some of the details of the differences that are described above may not be completely clear, but that is not a problem. The goal of the above discussion is to very shortly introduce some of the differences between coordination architectures. These differences will play an important role in the next sections, in particular Section 4.

3 The ToolBus coordination architecture

The ToolBus [8, 9, 26, 10, 25, 14] coordination architecture is being developed at the University of Amsterdam and the CWI (the Dutch National Research Institute for Mathematics and Computer Science). The name 'ToolBus' comes from the link to hardware busses. The ToolBus can be seen as the software equivalent: a software bus. Applications (which are called *tools*) that are connected to this bus are part of the system. Figure 1 gives an overview of an example ToolBus system. Note however that it is an *abstract* example that just shows all the important concepts.

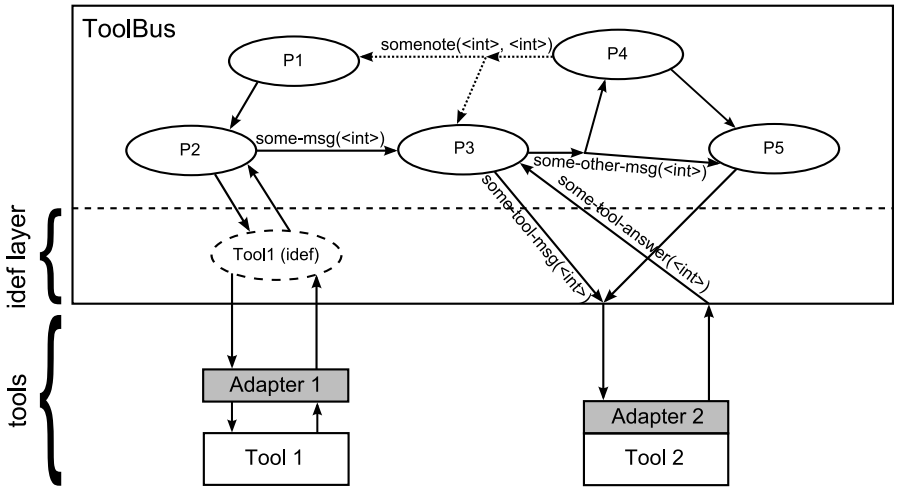


Figure 1: An example ToolBus system

It is important to note that within the ToolBus architecture, computation and coordination are completely separated, since the ToolBus itself does (in principle) not perform any computations, but only coordinates the communication. It can therefore be said that the ToolBus is control-driven and exogenous. The computations are done by the tools (the external applications). Tools are not allowed to communicate with each other directly, but only via the ToolBus. This is also visible in Figure 1. Since tools interface with the ToolBus via a strict interface, the ToolBus does not concern itself with the internals of the tools or the computations they perform. Thus, strict separation of computation and coordination effectively abstracts away from the computation part of the system.

The ToolBus is programmed with so called ToolBus scripts. These ToolBus scripts, or T scripts for short, are based on ACP (Algebra of Communicating Processes [4]). The T scripts contain *process* descriptions that describe all possible communication behavior of the tools. There may be one process for each tool, but there are no restrictions here; there may be extra processes and a single process may communicate with more than one tool. In Figure 1, the ellipses denote processes. Note that for Tool 1, there is only a single process that controls all communication with that tool. If the only goal of a process

is to interface between the tool and the rest of the system, it is called an *idef* (Interface Definition), as it defines the interface (behavior) of that tool. Tool 2 however, receives messages from both processes *P3* and *P5*. The use of an idef for each tool is currently common practice. T scripts support most of the process algebra operations. Beside atomic actions, these include sequential composition (`.`), choice (`+`), iteration (`*`), the delta action (`delta`) and parallel composition (||). Some extensions are included as well, like the introduction of (local) variables (`let ... in ... endlet`) and assignments and expressions on variables (`V := E`). See Table 1[1] for a more complete overview of the primitives that can be used in T scripts. The behavior of the whole system is defined as the parallel composition of all processes in the initial configuration (`toolbus(...)` keywords).

Figure 2 shows an example T script for the system of Figure 1 (except for the definition of processes *P1*, *P2*, *P4* and *P5*, which are omitted). In the first line, the definitions from the file `tool1.idef` are included. After that, process *P3* is defined. Three local variables are declared (variable `T` is of type `tool2`; variables `I` and `J` are of type `int`). The actual definition of the behavior of the process starts after the `in` keyword. First the process subscribes to a note, then it executes a tool. The rest is an iteration that consists of a choice. The first alternative is to receive a message, send a request to the tool, receive an answer from the tool and then send a message. The second alternative is to receive a note and then send a message. Since the iteration ends with a `delta` primitive that can never be chosen, the iteration iterates indefinitely. Almost at the end we see the definition of `tool2` with the command that needs to be executed to get the tool running. Finally, we see that processes *P1*, *P2*, *P3*, *P4* and *P5* should initially be created.

```
#include <tool1.idef>

process P3 is
  let T : tool2,
      I : int,
      J : int
  in  subscribe(somenote(<int>, <int>)) .
      execute(tool2, T?) .
      ( ( rec-msg(some-msg(I?)) .
          snd-eval(T, some-tool-message(I)) .
          rec-value(T, some-tool-answer(I?)) .
          snd-msg(some-other-msg(I))
        ) + (
          rec-note(somenote(I?, J?)) .
          snd-msg(some-other-msg(J))
        )
      ) * delta
  endlet

tool tool2 is {command = "./tool2"}

toolbus(P1, P2, P3, P4, P5)
```

Figure 2: An example T script

Unlike most other coordination architectures, the ToolBus has a solid formal foundation, since processes are defined in a process algebra syntax. Also, the ToolBus describes *all* the interactions between the tools, providing complete

[1]This table is based on Appendix E from [25].

Primitive	**Description**
`process ... is ...`	process definition
`tool ... is ...`	tool definition
`toolbus(...)`	ToolBus configuration (initial process creation)
`let ... in ... endlet`	local variables
`create(...)`	(dynamic) process creation
`delta`	inaction (deadlock)
P1 `+` *P2*	alternative composition (choice between alternatives *P1* and *P2*)
P1 `.` *P2*	sequential composition (*P1* followed by *P2*)
P1 `*` *P2*	iteration (zero or more times *P1* followed by *P2*)
P1 ‖ *P2*	parallel composition (communication free merge)
`snd-msg(...)`	send a message (binary, synchronous)
`rec-msg(...)`	receive a message (binary, synchronous)
`snd-note(...)`	send a note (broadcast, asynchronous)
`rec-note(...)`	receive a note (asynchronous)
`no-note(...)`	no notes available for process
`subscribe(...)`	subscribe to notes
`unsubscribe(...)`	unsubscribe from notes
`snd-eval(...)`	send evaluation request to tool
`rec-value(...)`	receive a value from a tool
`snd-do(...)`	send request to tool (no return value)
`rec-event(...)`	receive event from tool
`snd-ack-event(...)`	acknowledge a previous event from a tool
`rec-connect(...)`	receive a connection request from a tool
`rec-disconnect(...)`	receive a disconnection request from a tool
`execute(...)`	execute a tool
`snd-terminate(...)`	terminate the execution of a tool
`shutdown(...)`	terminate the ToolBus
`if ... then ... fi`	guarded command
`if ... then ... else ... fi`	conditional expression
V `:=` *E*	assignment
`delay(...)`	relative time delay
`abs-delay(...)`	absolute time delay
`timeout(...)`	relative timeout
`abs-timeout(...)`	absolute timeout
`printf(...)`	print formatted ToolBus terms to console

Table 1: Overview of ToolBus primitives

control over the tool communications. The behavior of the system is based on the semantics of process algebra, which makes it possible to formally reason about the communication within the ToolBus. By analyzing ToolBus communication, properties of the system can be proved formally.

Process definitions may include actions for starting and terminating tools (like `execute(...)` in Figure 2). The operating system commands that must be executed to start a tool are also defined in the T scripts. Another possibility is to connect to (or disconnect from) tools that are started independently of the ToolBus.

There are two methods of communication between processes inside the ToolBus: *messages* and *notes*. When using messages, one process (using the *snd-msg* action) sends a message and another process[2] (using the *rec-msg* action) receives the message. This communication is synchronous. To receive notes, a process must first subscribe to it. Then, when a process sends a note (using the *snd-note* action), all processes that are subscribed to that note will receive it (using the *rec-note* action). This is a form of asynchronous selective broadcasting. The dotted arrows in Figure 1 are an example of a note being received by two other processes.

Communication between processes and tools is different. Processes may send messages by using the *snd-eval*, *snd-do* and *snd-ack-event* actions, while tools may use the *snd-event* and *snd-value* actions. As mentioned earlier, there is no direct communication between tools.

All communication via the ToolBus is encoded in ATerms [11, 15]. ATerms are a language and platform independent way of representing data. Maximal subterm sharing is supported, which decreases memory use and allows for simple and fast equality checking. The very concise binary exchange format makes this term format ideal for communication. Examples of ATerms from Figure 2 include `somenote(I?, J?)` and `some-other-msg(J)`.

Tools that communicate via the ToolBus may be written in any programming language. To interface with the ToolBus, a language-specific adapter is needed. Such an adapter helps tools to support the message protocols of the ToolBus and it helps in the use of ATerms. This way the ToolBus can be used, without programmers having to be concerned too much with the details of the communication. Adapters for several languages, including Perl, Python and Tcl/Tk are available. Figure 1 shows two tools. Tool 1 uses a generic adapter for the Perl language. Tool 2 is written in C and uses two libraries (one for the ToolBus connection and one for ATerms). In the case of Tool 2, the adapter is sort of integrated in the tool. Tools may also be distributed over several machines with different hardware platforms. Tools interface with the ToolBus using TCP/IP sockets, but the details of this are hidden by the adapters. The ToolBus also hides other details of the communication (like for instance on which machines the other tools run) from the tools.

ToolBus scripts are static, they don't change during execution. The ToolBus

[2]The ToolBus doesn't explicitly support sending messages to a specific process. More information on this follows in the remainder of this section.

can be started with only a single script as it parameter, but scripts can include other scripts. The ToolBus executes scripts by interpreting them.

The ToolBus coordination architecture does not use named ports to connect parts of the system that may communicate. Instead, pattern matching on ATerms is performed by the ToolBus to determine which processes and tools communicate. As a consequence of this, it cannot (conclusively) be determined beforehand which process will receive a certain message. For example, in Figure 1 you see that process *P3* sends out ATerms with signature `some-other-msg(<int>)`. Both processes *P4* and *P5* can receive such a message and if both *rec-msg* actions are enabled at the same time, a non-deterministic choice will be made (and only one of them actually receives the message!). It is important to realize that user-defined data types are not present in the ToolBus, unlike in several other existing coordination architectures. However, ATerms are an encoding of user-defined data types. Therefore, even though user-defined data types may not be present in the syntax of T scripts, they are supported, since ATerms are used. Only a small set of built-in operations on ATerms is provided, which is sufficient, since only tools should manipulate data (and not the T scripts).

The ToolBus has been used for the renovation of the ASF+SDF Meta-Environment [24, 37, 38, 36], which was the reason the ToolBus was developed in the first place. Currently, it is one of the largest projects using the ToolBus system. It consists of almost 40 tools and about 300 process definitions, which is quite a lot. However, the ToolBus can also be used to support a multi-user game site with thousands of users[3]. This shows that the ToolBus is not limited to a single application domain, but can be used for very different types of applications.

Visit http://www.cwi.nl/htbin/sen1/twiki/bin/view/SEN1/ToolBus for the official ToolBus website. Extensive information on the first design of the ToolBus can be found in [8]. More information on applications that have been implemented by using ToolBus technology can be found in [26]. The second (and current) version of the ToolBus is the Discrete Time ToolBus, which includes several extensions, including time primitives. Extensive information on this second design of the ToolBus can be found in [9, 10]. A summary of the experiences that have been gained in the ToolBus project so far as well as a sketch of some preliminary ideas on how the ToolBus can be further improved, can be found in [14]. Information that is useful for ToolBus programmers can be found in [25]. The ToolBus is currently under active development. The first two versions were implemented in C. A new version is being implemented in Java.

Next, a bigger example system will be introduced. It is added to show what an actual ToolBus system looks like, to motivate some of the problems with the current ToolBus (Section 5.1) and to validate the solution to those problems (Section 8.2).

[3]In the Acknowledgments section of [14], it is stated that www.gamesquare.nl will be made ToolBus enabled. In Section 6 it is stated that the new Java implementation of the ToolBus aims at supporting such sites.

3.1 Compiler system example

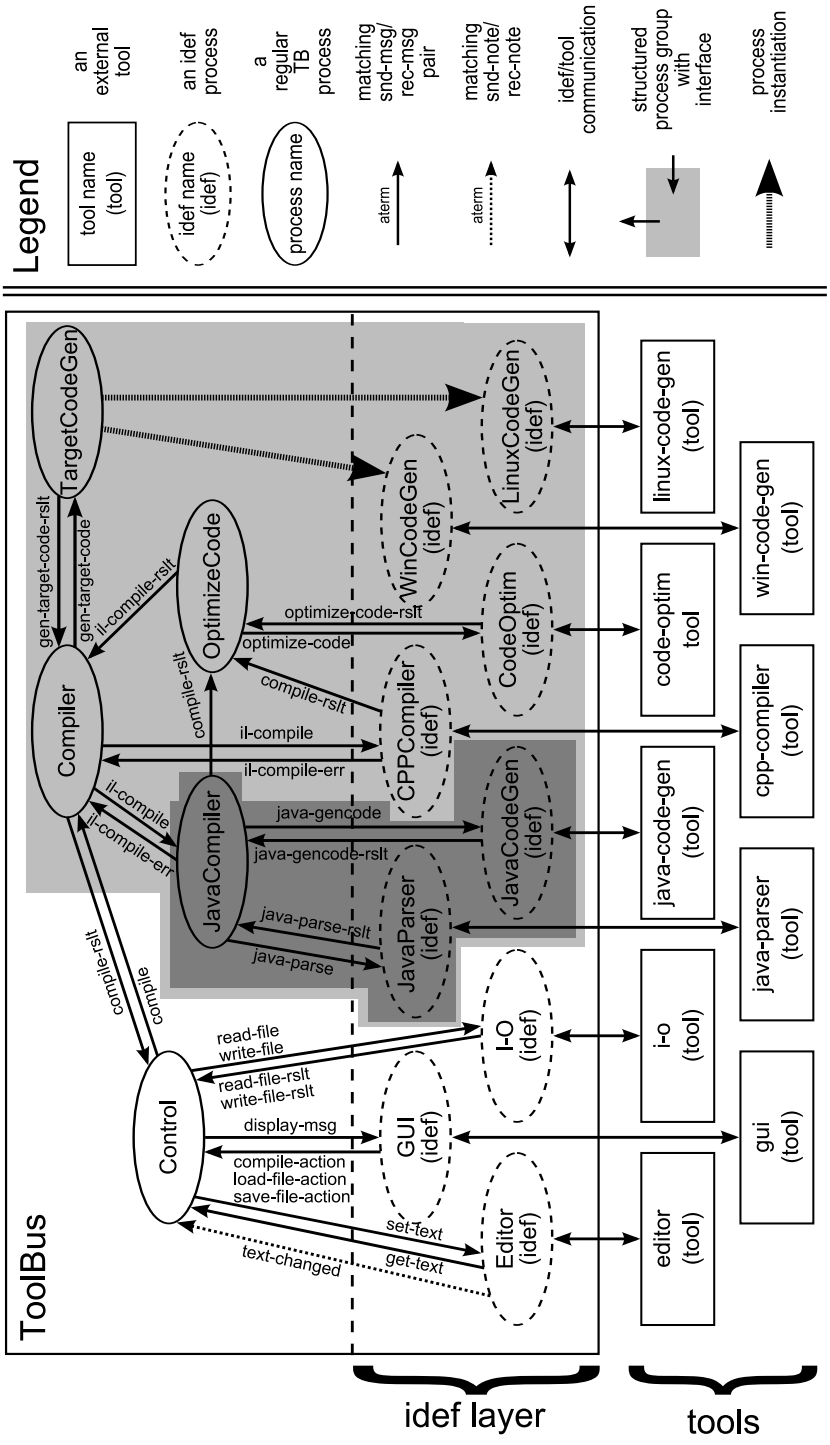


Figure 3: The compiler system example

It is now time to introduce a somewhat larger system: a compiler system that can be used to compile both Java and C++ source code for both Windows and Linux systems. The compiler system includes a code optimizer, a graphical user interface (GUI) and an (external) editor. See Figure 3 for an overview of the architecture of the compiler system (ignore the information related to 'structured process group with interface' for now). Note however, that the ATerm signatures of the messages are incomplete, as only the names of the messages are included.

There are nine tools, each with its own idef (process). The *GUI* tool/idef can signal the *Control* process that the user has requested an action (load a source file, save a source file or compile all source files). The *Control* process connects all the parts of the system. It will ask the *I-O* process to perform the saving and loading of the source files; it will send the loaded source code to the *Editor*; it will request the current code from the *Editor* before compilation; and it will ask the *Compiler* process to compile the code. The *Control* process can send messages (about compilation errors etc.) to the *GUI*, which will then display them. Also, the *Editor* can indicate that the source code has changed by sending a note.

The remaining part of the system is concerned with the actual compilation. The *Compiler* process sends the code to either the *JavaCompiler* or the *CPPCompiler*, which will create Intermediate Language (IL) code. The *CPPCompiler* is implemented by a single tool. The *JavaCompiler* is implemented by means of two separate tools, a parser (*JavaParser*) and an IL code generator (*JavaCodeGen*). Both the Java and C++ compiler can send out an *il-compile-err* message, or a *compile-rslt* message. The *OptimizeCode* process can receive *compile-rslt* messages, which include the IL code. The code optimizer will optimize the code and send it back to the *Compiler* process, which will then ask the *TargetCodeGen* process to generate target platform code for Windows (*WinCodeGen* process) or Linux (*LinuxCodeGen* process). The *WinCodeGen* and *LinuxCodeGen* processes are instantiated by the *TargetCodeGen* process.

4 Related literature

In this section, some other coordination architectures as well as related languages and systems that have been described in literature are discussed. Special interest will go out to the abstraction and modularization possibilities of those systems. At the end of this section there is an overview of all described coordination architectures and their properties.

4.1 Manifold

Manifold [1, 2] is a coordination architecture that was developed at the Center for Mathematics and Computer Science (CWI) in The Netherlands, just like the ToolBus. It is an implementation of a generic communication model, which is referred to as the Idealized Worker Idealized Manager (IWIM) model. This model enforces a strict separation of computation (by workers) and coordination (by managers). The 'idealized' means that workers process input, do some kind of computation and produce output, without knowing where the input comes from, where the output goes (this is also called 'anonymous communication') or how the system is build up (composed). For managers something similar holds; managers can create worker instances and (dis)connect them, without being concerned with what computation the workers perform and how they do it.

In the IWIM model, a *process* is a black box with well defined *ports* through which it can exchange information with its environment. There is a distinction between input and output ports. An input and an output port can be connected by a *stream*. Independent of the communication by streams, there is the notion of *events*. Processes need to register to receive certain events. Compositionality is a key concept of the IWIM model. A manager process that connects several worker processes together can be seen as a worker process by a higher-level manager. In this way, a hierarchy is introduced.

The Manifold coordination language can be used to create program modules (coordinator processes) that describe the interconnections (coordination) between the different processes that make up the application. The language is strongly-typed, block-structured, declarative and event-driven. Since connections can be dynamically created and destroyed, the architecture of a system constantly changes at runtime. A module encapsulates all that is declared inside, which corresponds nicely to the idea of processes being black boxes. So, there is a strong notion of abstraction.

The Manifold system consists of a library of built-in and predefined functions of general interest and a number of utilities, like a compiler and a runtime system. External processes may be written in any programming language and they may be running on different heterogeneous machines within a network. The Manifold system will take care of separate compilation and runtime mapping of modules to nodes.

Comparison with the ToolBus

The ToolBus and Manifold share a key goal: the strict separation of computation and communication. Also, both allow heterogeneous tools in a distributed environment.

However, there are also several striking differences. In the Manifold system, compositionality and abstraction are key concepts, while they are almost completely absent in the ToolBus. Furthermore, the ToolBus supports both synchronous and asynchronous communication, while Manifold only supports asynchronous communication[4]. Manifold programs have to be compiled beforehand, while ToolBus scripts are interpreted at runtime. Finally, the Manifold modules are described in what can be seen as a (specially designed) programming language, while ToolBus script have a more formal foundation, since they are based on process algebra.

4.2 Sophtalk

Sophtalk [20, 21] is a coordination architecture that was developed at the Institute National de Recherche en Informatique et en Automatique (INRIA) in France. The most important notion in Sophtalk is the *stnode* (Sophtalk node). There are two kinds of stnodes; an atomic stnode encapsulates an (external) tool and a non-atomic stnode encapsulates other (atomic and/or non-atomic) stnodes. In this way a strict hierarchy is introduced.

Stnodes can have multiple input and output ports, all of which have a name. All input and output ports with the same name on the same level[5] are connected by a so called bus line. This gives rise to multicast communication; when an stnode sends out a message on one of its output ports, it will be put on the bus line. It will then be received by all stnodes that have one of their input ports connected to that bus line. If the parent stnode has an output port connected to this bus line, it will propagate the message outward. If there are no stnodes 'listening' to the message, it will fall on deaf ears. Ports only have simple names and no types. This gives rise to some problems, as semantically equivalent ports with different names will not be able to communicate, while you would want them to. To cope with this problem, there is the possibility of renaming ports.

So, tools do not directly interact with the network; all communication goes via its encapsulating (atomic) stnode. Also, stnodes are defined by their external interface (their input and output ports). This results in their internal communication and composition to be completely encapsulated. Furthermore, this enforces a strict separation between computation and communication. Sophtalk only manages the composition of the system (and the communication within it) and performs no computations, while tools can perform computations but don't concern themselves with composition.

[4]The IWIM model does support synchronous communication, but this is not included in the Manifold implementation. This was a deliberate decision and it makes the processes less dependent.

[5]Two stnodes are on the same level if they have the same parent.

The Sophtalk system has a Le-Lisp implementation. It consists of a few packages. The first package concerns stnodes. There are functions to define stnode interfaces, create stnode instances, connect them, compose them, etc. The second one is the so called *stio* package. This package provides functionality that facilitates (transparent) external communication (with tools). The third and last package is the *stservice* package. This package provides an inter-process communication mechanism (based on TCP/IP sockets), that makes it possible for the *stio* package to work over networks.

Comparison with the ToolBus

Just like the ToolBus, Sophtalk enforces the strict separation of computation and communication. As a result of that, in both systems, tools cannot directly communicate. Sophtalk is highly event-driven; tools send messages about state changes, important events or requests for information at any time, which are then sent to the stnodes to be propagated to the rest of the system. The same can be said about the ToolBus, where the processes can be seen as stnodes. Both systems allow communication over networks (by using sockets).

There are however a lot of differences between the two systems. Sophtalk for instance has a clear notion of hierarchy and abstraction, while this is lacking in the ToolBus. Also, with Sophtalk it is possible to add, modify, substitute or remove tools from the system (at runtime) without disturbing global behavior. This is impossible in the ToolBus, as T scripts are static and cannot be changed at runtime. Furthermore, communication is different in the two systems. In Sophtalk ports with matching names can communicate (by means of bus lines) and ports can be renamed. In the ToolBus system, pattern matching on ATerms is used, and ATerms cannot be renamed[6]. Since the ToolBus has a single space of processes, pattern matching of sent ATerms involves all processes, while in Sophtalk, only the stnodes at the same level are involved in direct communication. Another difference in communication is that the ToolBus supports both synchronous (messages) and asynchronous (notes) communication, while Sophtalk only supports asynchronous communication (multicast). Also, Sophtalk only provides transport for messages, as stnodes only just receive messages and propagate them to other stnodes or external tools. The ToolBus however, performs pattern matching. It can extract a part of an ATerm, compose a new ATerm and send it, which is not possible in Sophtalk.

4.3 Field

Field [33, 5][7] was developed by Steven P. Reiss from Brown University somewhere in the 1980s. In [33], Reiss describes Field as an integrated programming environment that is extensible and can use old as well as new tools. Existing solutions weren't to his likings, so he created his own. He recognizes that the major contribution is, what he calls, the *integration framework*. And that is

[6]However, it is possible to add a new process that receives the message (ATerm), modifies it and then sends it out again.

[7]In [5] the EBI framework is introduced, which can be used to describe event-based software integration approaches. It is interesting in this context, since in that paper Field is (as an example) described using the EBI framework.

exactly what makes it interesting from our perspective.

Field, which from now on refers to the integration framework and not the programming environment that Reiss built on top of it, is based on 'selective broadcasting' (multicast). Client programs (called tools) register with a central server called *Msg*. They indicate the message patterns they are interested in. When a client sends a message to Msg, Msg checks which clients are interested and then sends the message to those clients. Messages can be sent both synchronously and asynchronously. If sent asynchronously, the sender continues immediately after sending the message; if sent synchronously, the sender waits for Msg to inform it that all the receivers have acknowledged the message.

Later versions of Field include several extensions. One such extension allows one to restrict the multicast to a subset of the tools. Another extension is the optional 'Policy Tool', which allows messages to be intercepted and user-defined actions (like replacing the message with another message or rerouting it) to be performed on them.

The Msg server runs as a separate Unix process. Each tool has its own client interface that forms the connection between that tool and the Msg server. Communication between client interfaces and the server goes via TCP sockets. This makes it possible for tools running on different machines to use a single Msg server. All messages are passed as strings. The client interfaces perform the required operations to make sure the received messages are interpreted and the correct procedure (with the correct arguments) of the corresponding tool is executed.

Comparison with the ToolBus

In the ToolBus, there are process descriptions that describe the possible communication behavior. In Field, all tools can basically communicate directly with each other (albeit via the Msg server). This is exactly the major difference between Field and the ToolBus; Field does facilitate the communication, but it doesn't really coordinate it; coordination rules and protocols must be implemented in the tools. In Field, coordination is therefore endogenous. This makes it harder to analyze the communication with Field than it is with the ToolBus. There is however partial abstraction of computation, as the Msg server doesn't perform any computation, but only facilitates communication.

Field can best be compared to the notes feature of the ToolBus. In the ToolBus, processes can subscribe to certain notes, which is like tools registering message patterns with Msg in Field. In Field, there is asynchronous and synchronous sending, while in the ToolBus, all notes are sent asynchronously. The ToolBus does support synchronous message sending, but it is point-to-point and not multicast.

The ToolBus doesn't have a 'Policy Tool' or anything similar, but it should be possible to implement something like it. The restriction of multicasting to only a subset of the tools is interesting and can be seen as a form of abstraction. There is no equivalent in the ToolBus.

The client interfaces of Field correspond in some way to the adapters in the

ToolBus system. However, the ToolBus system uses ATerms to communicate, while Field uses strings. Both systems use socket communication and allow tools to run on different machines. Heterogeneity is an important issue in the ToolBus, while it seems that Field pays no attention to it; it seems tools are only written in C. While it may be possible to write them in other languages as well, this is not mentioned.

4.4 CORBA

The Object Management Architecture (OMA) is the vision of the Object Management Group (OMG, http://www.omg.org) on component software environments (object-oriented systems). The heart of the OMA is the Object Request Broker (ORB) component that supports communication between heterogeneous components in a distributed environment. The Common Object Request Broker Architecture (CORBA) [42, 27, 31], standardized by the OMG, describes all aspects of the ORB in detail. Described here is version 2.0 of the CORBA.

As stated before, the ORB allows heterogeneous components to communicate in a distributed environment, but it does so in a transparent way. Clients can send requests to other objects (called the 'target objects'). The ORB hides the location, implementation and execution state of target objects; the requesting client doesn't know on which system the target object is located, how it is implemented (language, platform, etc.) and even if it's currently running or not (if the target object is not running, it will be started when needed). Also, the communication mechanism (like TCP/IP, local method call, etc.) is hidden. The client can simply request (from a Directory Service) an object reference (of a target object) by specifying the targets name or by specifying the targets properties. Note that the ORB doesn't include any Directory Services. These are located outside of the ORB in different parts of the OMA. Other functionality is pushed out of the ORB to different parts of the OMA as well, to keep the ORB as simple as possible.

In order for clients to know what requests it can make on an object, all objects specify their supported operations and types (their interface) in the OMG Interface Definition Language (OMG IDL). Such interface definitions closely resemble class definitions of C++ and Java. The OMG IDL however, is language independent. There are mappings for a wide variety of languages (including C, C++, Ada and Java) that define how OMG IDL constructs map to aspects of those languages. CORBA-based applications require knowledge of the interfaces of objects that it will communicate with. This information can be compiled into the application or applications can access the CORBA Interface Repository (IR) at runtime.

When a client has an object reference and it also knows the interface of the target object it can send a request (via the client-side stub that marshals it) to the client ORB. The client ORB will then make sure the request is delivered to the target ORB (via TCP/IP, local method call, etc). Then, finally, the target ORB will deliver the request to the target (via the target's skeleton that will unmarshal the request). The response is sent back in a similar way.

CORBA also supports Dynamic Invocation Interface (DII) for dynamic client request invocation (no client-side stub) and Dynamic Skeleton Interface (DSI) for dynamic dispatch to target objects (no target-side skeletons). The static approach allows clients to use Synchronous Invocation (client blocks waiting for the response) or One-Way Invocation (no response). Using DII, it is also possible to use Deferred Synchronous Invocation (the client can continue and will receive the response at a later time). DII however, has a hidden cost; it requires access to the IR, which may be a remote invocation.

CORBA also specifies Object Adapters (OAs) in general and the specific Basic Object Adapter, the glue between CORBA object implementations and the ORB. In later versions the Portable Object Adapter was introduced. The General Inter-ORB Protocol (GIOP), the Internet Inter-ORB Protocol (IIOP) and support for other environment-specific inter-ORB protocols (ESIOPs), were added in version 2.0. 'CORBA Messaging' and 'Objects By Value' further extend the architecture. For more information on these aspects of CORBA, see [42, 27, 31].

Comparison with the ToolBus

The ToolBus and CORBA are alike in that they both support communication between heterogeneous and distributed activities. Both hide a lot of communication details from the computational units. Also, both provide well-defined interfaces to the communication system.

There are also differences. CORBA supports only (asynchronous and synchronous) point-to-point communication. The target must be known (pre-compiled or dynamically obtained). This makes that CORBA is more of a communication architecture than a coordination architecture, as clients are explicitly aware of the targets they communicate with. The ToolBus supports both synchronous point-to-point and asynchronous selective broadcasting communication, for both of which the receiver is unknown. The ToolBus is a true coordination architecture. CORBA allows dynamic architecture reconfiguration, while in the ToolBus the architecture (T scripts) are static.

The ORB allows clients to access targets with in OMG IDL defined services and supports the communication. In the ToolBus, the T scripts strictly define all the possible interactions between the tools. This allows for a static formal analysis of the communication in the ToolBus.

CORBA is standardized and intensively used by industry. The ToolBus on the other hand, is more of an academic system that is not yet utilized as much in practice.

4.5 Service Component Architecture (SCA)

The Service Component Architecture (SCA) [19] is a set of specifications that describe a model for building applications, using a Service-Oriented Architecture (SOA). It is a collaboration of several dozen companies and all publications are royalty-free. A first version of the specification is published, but not yet final;

contributions and suggestions are still welcome. Obviously, implementations are not yet available either.

The SCA is a model that encompasses a wide variety of existing technologies, including component frameworks. Using SCA, it is possible to define services and assemble them together to serve a particular business need. Existing systems can be reused.

Components are the basis of the model. Components provide *services* and they require services from other components (these services are called *(service) references*). Services (and references) have interfaces, which may for instance be Java interfaces, WSDL portTypes or WSDL Interfaces [12]. Also, components can have *properties*, which are data values that influence the operation of the components. The SCA can be used to *configure* the system, by connecting (called *wiring* or *binding*) services to references and by providing values for the properties. Bindings come in many forms, including as an SCA service, as a Web Service, as stateless session EJB (Enterprise Java Bean [28]) and as CORBA IIOP (see also Section 4.4). Components themselves may be implemented in a variety of languages, including Java, C++, BPEL, PHP, JavaScript, XQuery and SQL. A hierarchical structure is possible, since components may be composed of other components. Also, services and properties may be deferred to sub-components.

So, the SCA allows the use of many different existing technologies, making it possible to choose the best solution for each element of the system. SCA assemblies (called *Composites*) may contain components, services, references, properties and the wiring that connect them. SCA uses an XML file format to specify this (static) configuration of the system. The SCA runtime also allows for the dynamic reconfiguration of systems.

Complementary to the SCA, there is Service Data Objects (SDO) [7, 6]. SDO is a complete architecture for data types that allows heterogeneous and distributed data access and provides static and dynamic APIs, framework support, common data patterns and decoupling of application data code from data access code. The use of SDO is strongly recommended, but not enforced.

Comparison with the ToolBus

The SCA is business oriented. It focuses on providing and using services, instead of the actual communication. The configuration of the system is described (for instance, service A is provided by service reference B). In the ToolBus, T scripts describe the actual communication behavior and not who communicates with whom, since that is determined at runtime by pattern matching.

Companies can create their own implementations of the runtime system of the SCA, as long as they satisfy the specifications and guidelines. The ToolBus is just a single execution system, although (in theory) other ones could be created.

The SCA has a strong hierarchical system composition, while in the ToolBus all processes (defined in the T scripts) live in a single space. Also, SCA implementations may support dynamic reconfiguration, while the ToolBus doesn't support it. The ToolBus however has a solid formal foundation that allows for

analysis of the communication.

4.6 Koala

The Koala Component Model [40, 41, 39] has been developed by Philips Research Laboratories and the London Imperial College. With its strong focus on consumer electronics, it has already been successfully used by Philips for several years in the development of software for televisions.

Components are pieces of software that communicate to their environment through their *interfaces*. An interface defines the functionality that a component *provides*, as well as the functionality it *requires* in order to do so. Interfaces are described in an Interface Description Language, which resembles COM and Java. There is a distinction between *interface type*, being a reusable interface; and *interface instance*, the use of such an interface in a component. Note that components are completely unaware of the configuration in which they will be used. Similarly to interfaces, there are the notions of *component type* and *component instance*. A configuration is created by instantiating components and *binding* (connecting) their interfaces. Components may be instantiated more than once. Note that a requires interface must be bound to exactly one provides interface, while a provides interface may service multiple (possibly zero) requires interfaces. A requires interface must always be of the same type or a subtype of the provides interface it is bound to. If interfaces don't match directly, light-weight glue components (called *modules*) can be used. It is possible to create *compound components* that contain other components, thereby creating a hierarchical structure. Components can have properties, which are usually called *diversity interfaces*. They are implemented by means of standard requires interfaces and they can thus be configured (bound) outside of the component itself. This means that the properties can be set outside of the component. Through *function binding*, multiple provides interfaces can service a single (extended) requires interface. *Switches* can be used to make dynamic servicing possible; properties control the dynamic selection of one of several provides interfaces that will service a requires interface. Finally, *optional interfaces*, which are requires interfaces that don't necessarily have to be bound to a provides interfaces, may be added to components.

Components must be implemented in C and they are subject to strict naming conventions. The Koala compiler reads the configuration (written in a Configuration Description Language) and interface descriptions in order to generate header files that contain bindings in C. A component should only include Koala generated header files. A build process to compile the system (including its components) is also part of Koala. The compiler is quite intelligent as it can optimize code. If for example a static property is used in a switch, only one alternative can be chosen. The actual used alternative is then bound by the compiler and the other optional bindings are optimized out.

Comparison with the ToolBus

Both the ToolBus and Koala make a clear distinction between computation and coordination. However, the list of differences seems endless. The fact that the

ToolBus and Koala were designed with completely different goals in mind, is probably the reason for this. The ToolBus was designed with heterogeneity and distributivity in mind and focuses on the integration of all existing tools. Koala focuses on consumer electronics components written only in C. Furthermore, Koala has a clear hierarchical structure, which is lacking in the ToolBus. Koala uses compilation to bind C functions, while the ToolBus uses interpretation of T scripts and pattern matching on messages in ATerm format. Consumer electronics usually have limited hardware resources and that clearly has its impact on Koala, for example in the optimization of the compiler.

4.7 Overview

An overview of the properties of all the systems described in this section, as well as the ToolBus system described in the previous section, can be found in Table 2.

The columns of the table correspond to the properties of coordination architectures as discussed in Section 2. The *Integration* column describes how the integration is performed and how the communication between parts is organized. The *Abstr. of comput.* column indicates to what extent the coordination framework separates computation and coordination, as well as how the details of the composition are hidden from the computational units. The *Abstr. of commun.* indicates if and how the systems abstract away from the low-level details of the communication. The *Structure* column indicates if there are methods of structuring the composition within the coordination architecture. The *Formal foundation* column indicates if they have a formal basis to describe the communication that allows for analysis of the communication. The *Execution* column indicates if compilation is required or that scripts are interpreted at runtime, where the data conversions are performed (if any) and other details of the execution.

Interesting to point out is that CORBA doesn't have full abstraction of computation. Also, there is a lot of diversity in the amount of structuring possible; the ToolBus is one of the few systems that doesn't have a dynamic architecture; and Field is the only endogenous system. Communication (as in (a)synchronous and broadcast vs. point-to-point) that is possible differs significantly between the systems. Also, the implementation (execution, language, data) shows quite some differences. The SCA doesn't even have an execution environment; that part is left unspecified. Implementers of the runtime system (several of the companies contributing to that project) may each fill in those details themselves.

If we compare the ToolBus with the other systems, we see that the ToolBus fully supports heterogenic tools. It lacks structure and a dynamic architecture. However, the latter, combined with the formal foundation, makes it possible to analyze the communication and prove properties of that communication. This is one of the defining features of the ToolBus. In addition, ATerms are language and platform independent as well as resource efficient, unlike the data types of some other architectures. Finally, the ToolBus allows one to define the communication behavior of the tools; in the T scripts the interaction can be

formalized. Other systems don't have such control over the communication. In CORBA for instance, clients may join at any time, communicate with anyone they like and then leave again. Other systems, like Field, merely just facilitate the communication. The ToolBus however, allows one to fully coordinate all interaction!

The conclusion is therefore that the ToolBus is a unique and useful coordination architecture. One of the biggest problems is the lack of structure (on processes). In the next section the structure-related problems of the ToolBus will be described in more detail.

System	Integration	Abstr. of comput.	Heterogeneity	Distributivity	Abstr. of commun.	Structure
ToolBus	T scripts + pattern matching on ATerms	Full (adapters)	Yes (adapters, ATerms)	Yes	Yes (adapters)	None
Manifold	Managers (coordinator processes) + connected by streams	Full (IWIM model)	Yes (platform) + No (just C)	Yes	Yes (linker etc)	Hierarchical
Sophtalk	Stnodes + bus line	Full (encapsulation by stnodes)	Limited (Le-Lisp + Unix shell)	Yes	Yes (stio + stservice packages)	Hierarchical
Field	Msg server + registration	Partial (endogenous)	Unknown (probably just C)	Yes	Yes (client interfaces)	Limited (subset restriction)
CORBA	ORB + targets	Partial (clients know targets)	Yes (OMG IDL)	Yes	Yes (ORB)	Limited (OMG IDL)
SCA	Composites + wiring	Full	Yes (SDO)	Yes	Yes (wiring)	Hierarchical
Koala	Components + bindings	Full (interfaces)	None (just C)	No	Yes (header files)	Hierarchical

System	Dynamic architecture	Formal foundation	Data/control-driven	Endo/exogenous	Application domain	Implementation status
ToolBus	No (static T scripts)	Yes (process algebra)	Control-driven	Exogenous	Generic	New Java version under development
Manifold	Yes	Yes (two-level transition system)	Control-driven	Exogenous	Generic	Completed
Sophtalk	Yes	None	Control-driven	Exogenous	Generic	Completed
Field	Yes	None	Control-driven	Endogenous	Generic	Completed
CORBA	Yes	None	Control-driven	Exogenous	Generic	Existing standardized versions (new versions expected)
SCA	Yes	None	Control-driven	Exogenous	Generic	Specification not yet final
Koala	Partial (switches)	None	Control-driven	Exogenous	Consumer electronics	Completed

System	(A)synchronous communication	Execution	Language	Data
ToolBus	Synchr. p-to-p (messages) and asynchr. sel. broadc. (notes)	Interpretation of T scripts + adapters	T scripts	ATerms
Manifold	Asynchr. p-to-p (streams) and asynchr. sel. broadcast (events)	Compilation + runtime system	Manifold language	Bit-strings + references
Sophtalk	Asynchr. sel. broadcast (bus line)	Execution of Le-Lisp commands	Le-Lisp	Le-Lisp data types
Field	Asynchr./synchr. sel. broadcast (via Msg server)	Msg server + client interfaces	N/A (no real coordination, just communication)	Strings
CORBA	Asynchr./synchr. p-to-p (targets, DII, DSI)	Compilation (clients) and ORB execution	OMG IDL	OMG IDL types
SCA	Asynchr./synchr. p-to-p (wiring)	Unspecified	XML files (configuration)	SDO
Koala	Synchr. p-to-p (function calls)	Precompiled	IDL/CDL + C	C data types

Table 2: Overview of the properties of the described coordination architectures

5 Problem introduction

This section is about some of the (structure-related) limitations of the ToolBus, as well as the requirements on the solution to the problems related to those limitations.

5.1 The need for additional structure

The ToolBus runs T scripts, which consist of several process definitions that together describe all possible communication within the system. There is no structure on the collection of processes; all processes live in a single process algebra space and are combined using the process algebra parallel composition operator.

There is a possible efficiency problem that arises here. When the number of processes increases (possibly, but not necessarily, due to an increase in the number of tools), the overhead of pattern matching also increases. This is the case, since more processes (most probably) means more *snd-msg* and *rec-msg* actions, which also means that the number of pairs of them increases. So, more matching needs to be done to find out which *snd-msg* and which *rec-msg* actions can possibly communicate. Even though the matching algorithm is implemented efficiently and runs very fast, in the worst case performance may degrade exponentially as systems become larger!

Another problem that manifests itself when systems become larger, is that those systems become harder to understand. For systems written in mainstream programming languages like C++ and Java, it is usually easy to see what is going on in a small module (or class) with only a few methods. But as the number of methods increases, the module becomes harder to understand. It is then common practice to decompose it into several smaller modules (or classes), that are then easier to understand. Methods with similar functionality and/or strong dependencies are grouped together in modules. It is even better when the large module is decomposed into several components. Then the internal details of the components are hidden from the outside and communication between components is limited to what is supported by their interfaces (components are so called 'black boxes'). This not only makes them easier to understand, but it also decreases the number of dependencies (decreases coupling) and improves maintainability. When the number of ToolBus processes increases, things also become harder to understand, since in principle all those processes can communicate with each other. It is possible to spread the processes over several T scripts and create a new T script that includes all the other ones. This is similar to the situation of decomposing a huge module into several smaller ones. However, there is no abstraction of the internals of the smaller modules/scripts. There is currently no way to decompose a large group of ToolBus processes into some sort of 'components', similar to what is possible in modern programming languages. In Figure 3 two components[8] of the collection of processes (for the

[8]Components are called 'structured process groups' in that figure. The term 'Structured Process Group' will be introduced in Section 5.2.

compiler system example) are indicated: the whole compiler component and the Java compiler (sub-)component. The compiler component has only two external messages (to Control), which means it has few dependencies. Also, there is quite some communication inside that component, making it highly cohesive. The compiler component thus contains a clearly defined part of the system, making it easier to oversee the global structure of the system. The details of the compiler component are hidden from the outside, which has no interest in its internals (communication, structure, etc.).

A related problem is that of replacing parts of the system. If a subsystem needs to be replaced by a different subsystem with the same functionality, it would be nice if the old parts could just be removed and the new parts added. In modern programming languages, components with similar functionality and the same interface can be interchanged easily. In the ToolBus, with tools, this is quite easy as well, as they have clearly defined interfaces (idefs). For processes in the ToolBus, this is more difficult; the internal details of neither the old nor the new subsystem are hidden from the rest of the system. This may cause serious problems when interchanging them without investigating the extent of that interchange. The next paragraph contains some more details on this. The same problem as for replacing a part of a system goes for updating a part of a system. Replacing and updating subsystems are important actions in the evolution of a system. For the compiler system example, having a compiler component makes it easier to replace the entire compiler part of the system; we can just replace that component with an equivalent one (with matching external interface). When there are no components, it is quite a puzzle to see what processes have to be removed for all compiler functionality to be removed from the system. In such a case, the biggest problem is to find all dependencies of the processes you remove. Since pattern matching is used for communication, it is not immediately clear what the dependencies of the removed processes are.

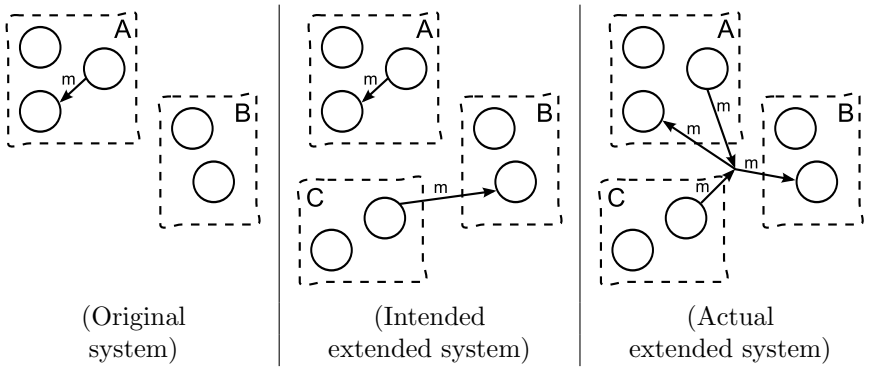


Figure 4: Message clashes in the ToolBus

Another problem that is more likely to occur when systems become larger, is the problem of name clashes of messages. Suppose there exists a system that consists of two parts (subsystems), say A and B, both of which consist of several ToolBus processes. In A, there is a message m that is used only internally among processes in A. This situation is depicted in Figure 4 (on the left), but note that all communication other than message m is left out for clarity. Then

the system is extended with a new subsystem C, which also consists of several processes. Subsystem C is created by a different programmer, who implements communication between subsystem C and the existing subsystem B to be by means of a message m. The intended behavior of the system after C is added is depicted in the same figure (in the middle). Since all processes exist in a flat space, message m sent by C may not be communicated to B, but to A instead! The actual behavior of the system is once again depicted in the same figure (on the right). So, in this example we see that, when adding a new subsystem that communicates with an existing subsystem, internal messages of a completely unrelated subsystem interfere in the communication. Obviously, in small systems this is not really a problem, as it is probably detected early on and it can be corrected easily. However, when systems become larger and larger, one may not even realize such a problem exists until it manifests itself. That is, *if* it manifests itself, since it may only be a problem under certain very rare circumstances. Therefore, in those cases the problem may go unnoticed, leaving one with an incorrect system; and if it is noticed, it may be hard to track down the actual problem.

When several tools communicate via a single ToolBus and one of them crashes, the others can continue to run. This is true, since all tools run isolated from each other and don't communicate directly. The process (or processes) that communicate with the crashed tool may deadlock, but the remaining processes and tools can (in principle) continue to function. This means there is a good basis for building dependable software systems with the ToolBus. There is a strong interest in building dependable software systems, especially in industries related to embedded systems. Dependability is also one of the main reasons for Philips to be interested in this project. However, currently there is no way to monitor tools or to reset them if they have crashed, which is needed for real dependability. Also, among other things, we should be able to detect and resolve the deadlocks mentioned earlier. If the ToolBus were to be extended with monitoring and resetting capabilities, it would be nice if groups of ToolBus processes could be monitored and controlled as one entity. However, as we have previously seen, there is currently no way to introduce some sort of structure into a large group of processes. In the compiler system example, it would be nice to be able to monitor the entire compiler component as a single entity and reset it in its entirety (if and when needed).

One of the major differences between the ToolBus and other coordination architectures is that in the ToolBus *all* interaction between the tools is described in a formal matter, thus allowing formal analysis of the communication. However, when systems become larger, the communication usually increases. Since in principle all processes can communicate with each other, the analysis of the communication becomes more difficult. Adding structure to the collection of processes would make it possible to analyze the communication of groups of processes locally, which is easier to manage. Also, it would make it possible to analyze the communication at different levels. However, there is currently no way to group processes and introduce a hierarchy. Looking at the compiler system example, we see that the compiler component has a very limited interface (only two messages). Hiding the internal communication from the outside would make it possible to analyze the compiler component in isolation.

You may have noticed that most of the above limitations/problems manifest themselves more prominently when systems become larger and the number of processes increases. Systems with dozens (or even hundreds) of tools are considered to be large, as well as systems with several hundreds (or even thousands) of processes. We are mainly interested in systems that are large in the number of processes and less so in those with large amounts of tools, although it is plausible to assume a relation to exist between them. The great number of processes causes problems, because they all live in the same space and there is no structure among the processes. So, the lack of structure in the collection of processes is the main issue that needs to be addressed.

5.2 Introducing Structured Process Groups

We have seen what structure-related problems exist in the ToolBus. As a solution to these problems, 'Structured Process Groups' will be introduced into the ToolBus system. A 'Structured Process Group' is a group of ToolBus processes that run in 'relative isolation'; it is an abstraction over groups of ToolBus processes. These are the requirements that an implementation of structured process groups should satisfy:

R1 *Hierarchy* It should be possible for structured process groups to contain other structured process groups, thereby introducing a hierarchy on structured process groups.

R2 *Abstraction* Internal details of a structured process group should be hidden from the outside. This means that communication that is internal to a structured process group should not be observable from the outside. Also, the composition of a structured process group should be kept internal.

R3 *Interface* Structured process groups should have a clearly defined (external) interface.

R4 *Reuse* It should be possible to reuse a structured process group in a different system.

R5 *Semantics* If possible, the introduction of structured process groups should not change the semantics of the ToolBus.

R6 *Backwards compatibility* If possible, compatibility with old T scripts should be maintained.

R7 *Formal foundation* It should still be possible to describe the behavior of the system in process algebra, in order not to lose the formal foundation of the ToolBus system.

R8 *Performance* An implementation of structured process groups should have reasonable performance. That is, the introduction of structured process groups should not decrease performance of ToolBus systems too much. Preferably, any decrease in performance is either not noticeable by the end-user, or so small that is doesn't practically hinder the use of ToolBus systems.

R9 *Name clashes* Name clashes (of messages) are a serious problem. A solution to this problem must be conceived. This may be in the form of structured process groups, but it may also be an independent solution.

R10 *Dependability* As noted in Section 5.1, the ToolBus has a good basis for building dependable software systems. However, monitoring and resetting features are not yet present. Both *structural isolation* (see requirements R1 and R2) and *runtime isolation* (also called *physical isolation* or *execution isolation*) are prerequisites for implementing such dependability features. The implementation of dependability constructs is not a part of this project. However, any solution implemented as part of this project should facilitate the future implementation of dependability constructs. Dependability is something to keep in mind.

So, why these requirements and not some other ones? Well, the need for hierarchy (or structure in general) and abstraction should be clear from Section 5.1. The reason for interfaces is (among others) to make reuse possible/easier and reuse itself is useful in decreasing development time as well as reducing costs. Keeping the semantics unchanged makes backwards compatibility easier to achieve. Backwards compatibility in itself is very important, since we don't want to discard our existing systems. That we want to keep the formal foundation is not surprising as it is one of the key selling points of the ToolBus. As with any software product, performance is an issue. Name clashes are a specific problem and a solution to them would certainly be useful. Finally, dependability is something to keep in mind as it is one of the driving forces behind this project.

The choice for a hierarchical structure is rather specific. We could have just opted for groups of processes. However, that would be a hierarchy of fixed depth (groups and processes). With a hierarchical structure, we create the freedom to have hierarchies of any depth. This will however have consequences, as we will see later on.

Note that requirements R5 and R6 state "If possible, ...", but what if it's not possible? Well, in that case we allow changes if they are either necessary or clearly preferable. If this breaks backwards compatibility, then so be it. However, in that case, it may be possible to come up with a way to (partially) convert old T scripts into the new format such that old systems can still be used. The choices that are made will have to be based on solid arguments that substantiate the decisions.

It is impossible to predict how the future dependability features will be implemented. This project will only be concerned with making processes structurally isolated.

6 The solution: hierarchy, abstraction, namespaces and relays

In the previous section structured process groups were introduced. Many alternatives for specifying their structure were considered, several of them inspired by systems from Section 4. Some of these alternatives included: putting the hierarchy information in the name of the process (as a prefix), introducing a new keyword for defining structured process groups (possibly in different files) and allowing for nested process definitions. While considering the alternatives, the realization that in some way structured process groups and processes are the same thing became stronger and stronger (both for instance send and receive messages). It was therefore only logical to see if both concepts could be unified into a single concept.

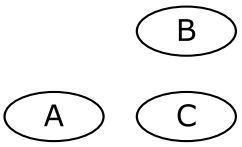
The challenge was then to turn processes into structured process groups. To that end, an (informal) comparison between processes in their current form and Koala (from Section 4.6) was performed. It revealed that introducing a hierarchical structure on processes (like in Koala) would be essential. It also led to the introduction of a communication restriction that could enforce abstraction. Finally, in order to solve name clashes, Koala interfaces were investigated, which led to a concept of namespaces.

A hierarchical process structure combined with the communication restriction and namespaces seemed a promising solution and it was further investigated. In the remainder of this section, all the aspects of that solution are described in full detail.

6.1 Hierarchical processes

6.1.1 The current situation

Currently, instantiation of processes is achieved by adding `toolbus(...)` lines to the T scripts. Upon execution of a ToolBus script, the ToolBus executable gathers all those lines (by following the `#includes`) to find out which processes should be instantiated. By including a certain T script, you automatically include all instantiations present in that file! This means that instantiation is rather static. It should be noted however, that while it's impossible to prevent the instantiation of processes contained in the `toolbus(...)` lines, it is possible to instantiate more processes dynamically, by means of the `create(...)` action, or by using process calls. After collecting, the ToolBus will instantiate all collected processes (with the parameters that it also collected). The instantiated processes will then live in a single space and there is no hierarchical structure. An example of a simple system, including the corresponding T scripts, is depicted in Figure 5. Note that it is an abstract example and the system has no meaning other than to explain new concepts. The system has three processes (A, B and C). In this example system all communication is omitted. Also, the definitions of the processes are omitted, since communication is irrelevant at this point.



(System overview)

```
#include <cur2.tb>

process A is
  /* omitted */

toolbus(A)
```

(cur1.tb)

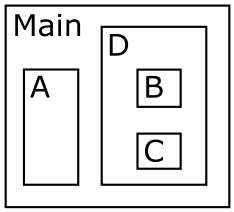
```
process B is
  /* omitted */

process C is
  /* omitted */

toolbus(B, C)
```

(cur2.tb)

Figure 5: Example of process instantiation in the current ToolBus

6.1.2 Introducing hierarchical processes

The idea of a hierarchical process structure is that processes can instantiate other (sub-)processes. The instantiating process is called the *parent process* and the instantiated process is called the *child process*. Since the child processes can also instantiate other (sub-)processes, this results in a hierarchical structure. Processes can instantiate all the processes they like and they can even instantiate a single process multiple times. This creates a lot of freedom. The `toolbus(...)` construct will no longer be used. Instead, processes are instantiated by means of the already existing `create(...)` action. Instantiation of the child processes will often be the first thing a process does. However, this is not a restriction, as a process may (still) instantiate processes at any time. Note that it was already possible to have processes create other processes. However, now we enforce the use of the `create(...)` action, since we no longer allow the use of the `toolbus(...)` keyword. Also, we now keep track of the resulting hierarchy, where as before newly created processes were just put in the large unstructured collection of processes. Also note that this approach solves the problem of instantiations being rather static (as just described in Section 6.1.1).



(System overview)

```
#include <new2.tb>

process Main is
  let Pid: int
  in  create(A, Pid?) .
      create(D, Pid?) .
      /* omitted */
  endlet

process A is
  /* omitted */
```

(new1.tb)

```
process D is
  let Pid: int
  in  create(B, Pid?) .
      create(C, Pid?) .
      /* omitted */
  endlet

process B is
  /* omitted */

process C is
  /* omitted */
```

(new2.tb)

Figure 6: Example of process instantiation when using hierarchical processes

Now that we have a hierarchical process structure, we can modify the example system of Figure 5 by adding more structure. Suppose that processes B and C together perform some function. We can then group them together as children of a new process (D). In doing so, we get two processes (A and D) at the top of the hierarchy. However, only a single top level process is allowed as we will

see in Section 6.1.5. Therefore, we introduce a new process (*Main*), which will instantiate both processes *A* and *D*.

The result is a hierarchical system, with process *Main* at the top of the hierarchy. An overview of the system as well as (partial) T scripts can be seen in Figure 6. Figure 7 shows the hierarchical process structure (instantiation tree) of the system. We can clearly see that processes *B* and *C* are children of process *D*, while processes *A* and *D* are in turn children of process *Main*. The important thing to remember from this example, is that we can now put coherent groups of processes together as child processes of another process, thereby creating a *subsystem* (or *component*).

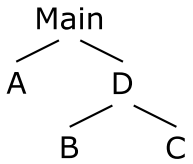


Figure 7: Hierarchical process structure (instantiation tree)

Besides full control over what processes will be instantiated at what time, the hierarchical structure doesn't have any direct benefits. It will however play an important role later on, when the hierarchical structure will be used to support new features. The hierarchical structure is also called *logical structure*. Both refer to the structure of process instantiation.

6.1.3 Note on `toolbus(...)` construct

The removal of the `toolbus(...)` construct doesn't limit the expressional power of the ToolBus system. Upon execution of a ToolBus script, the current ToolBus collects all `toolbus(...)` constructs and then instantiates all the processes indicated by those constructs. Instead of such a `toolbus(...)` construct, `create(...)` actions could have been used. However, during the development of the original ToolBus, the decision was made to include an explicit construct for the initial creation of processes. The set of all `toolbus(...)` constructs is nothing more than syntactic sugar for a single process that creates the other ones. This insight is used in implementations of the ToolBus and will also be used in Section 7.5. Note that when `create(...)` actions are used exclusively, no process will be instantiated initially. See Section 6.1.5 for more on this issue.

6.1.4 Dealing with cycles

Since processes can freely instantiate (create) whatever processes they like, there is the danger of getting an infinite cycle of instantiations. If for example (in Figure 7) process *D* would also instantiate process *Main*, then we would get the following infinite cycle: '*Main* creates *D* creates *Main* creates *D* creates

Main...'. Note that something similar is possible in the current ToolBus, by having cycles in the `#includes`.

It is up to the developer of the system to make sure there are no such cycles. The ToolBus executable however, could create a directed graph, which would contain a node for each process as well as edges for all processes to each of the processes they instantiate. Note that cycles may consist not only of process instantiations, but also of process calls, so edges will have to be added for those as well. This graph could then be checked for cycles and the ToolBus could warn the user if such cycles are found.

It should be noted however, that the existence of cycles isn't always a problem. If for instance a process were to call itself recursively, we would have a cycle. By making sure that the recursion ends (well-founded recursion), the cycle is no longer infinite and thus there is no problem.

6.1.5 Top level process

As mentioned before, we only allow a single process at the top of the process hierarchy. This process is called the *top level process*. The top level process represents the complete system. When executing a system, the ToolBus simply instantiates the top level process, which will then instantiate other processes, which will also instantiate other processes, and so on.

But how do we indicate which process is the top level process? There are two options. The first option is to supply an extra parameter to the ToolBus executable that specifies the name of the top-level process that must be instantiated. The second option is to always have one process with a fixed name (for example process *Main*) that starts the instantiation. This is similar to the way the `main(...)` procedure is used in several programming languages.

In the end, a combination of both seems to be the most appropriate. If no process name is supplied as top level process, then by default the *Main* process will be instantiated. If however, a process name is indeed supplied, the process with that name will be the top level process. This way we have full control over what process will be at the top of the hierarchy. How to actually supply the name of the top level process is an implementation issue, but it would make sense to add is as an optional parameter to the ToolBus executable.

This approach to the top level process gives a lot of freedom. Assume for instance that we have two separate systems, one with a top level process called *Main* and the other with a top level process called *System*. Also assume we want to combine the two systems into a single new system. We then create a new top level process definition (with a unique name) and have that process instantiate both original top level processes. Obviously, some interaction between the two systems will have to added as well, but should be clear that combining systems is quite easily achieved by adding a new top level process at the top of the new system. However, if both original systems have a top level process called *Main*, then a name clash of process names occurs. More on this in Section 11.4. Also, a more extensive discussion on the decision to have only one top level process

can be found in Section 6.2.5.

6.2 Hierarchical processes and communication

We have just introduced hierarchical processes. However, in none of the examples there was communication.

6.2.1 Current situation

In the current ToolBus, communication occurs by pattern matching on ATerms. All processes can potentially communicate with each other. In Figure 8 we see (on the left) the same example system as we saw earlier. On the right, we see the hierarchical version of the system. However, now process C communicates with both process B and process A.

(Current ToolBus version) (Hierarchical version)

Figure 8: Example of a ToolBus system with communication

6.2.2 Abstraction

One of our requirements is abstraction. We want to hide *all* internal details of processes. For instance, we want to hide the fact that process D contains two child processes (B and C). Also, we want to hide all internal communication of process D. Thus, the messages *m1* and *m2* sent by process C should be kept internal to process D. In Figure 8 (on the right) we see that his is not the case, since process A (which is outside of process D) receives a message from process C (which is inside of process D). To achieve the required abstraction, we have to restrict the possible (direct) communications. To that end the following rule is introduced, which will be referred to as the *communication restriction*:

A process may only[9] (directly) communicate with:

- Its parent process.

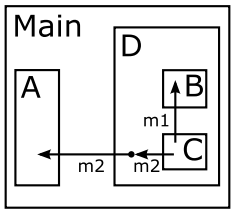
[9]Note that it is not possible for a process to communicate with itself, even if it has matching *snd-msg* and *rec-msg* actions that are enabled at the same time (due to the use of the $\|$ operator). This is a deliberate design-decision made by the designers of the ToolBus system.

– All other child processes created by its parent process (we will refer to those processes as the *siblings*).
– The child processes it itself created.

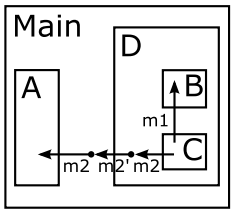
This rule restricts the group of processes that any single process can (directly) communicate with, hence its name. Currently, if a *snd-msg* and *rec-msg* action have matching ATerms, they can communicate. Now, because of the communication restriction, the situation changes a bit. If such a communication violates the communication restriction, then those two actions no longer match (thus *enforcing* the rule)! Note that none of this means that a send action always has a single receive action that it will communicate with, as is the case in many other communication architectures. Pattern matching is still used, only the communication restriction is applied on top of it. So, communication is only possible with the parent (one level up in the hierarchy), with the siblings (on the same level in the hierarchy) and with the children (one level down in the hierarchy)[10]. Communication can never go more than one level up or down the hierarchy, thereby enforcing abstraction. This is the exact reason the rule is introduced; it enforces abstraction but doesn't limit communication in any other way. As we will see later on, this abstraction has several benefits.

6.2.3 Chaining

The restriction just introduced has the consequence that the message *m2*, sent by process C in our example, can no longer be received by process A, as such a communication would violate the communication restriction. The parent of process C (process D), the siblings of process C (process B) as well as the children of process C (none exist) may receive message *m2*. But not process A, which is a sibling of the parent of process C.



(Chaining solution 1)



(Chaining solution 2)

Figure 9: Examples of chaining

Figure 9 shows two possible solutions. In the first solution, process C sends message *m2*. It is received by process D (indicated by a dot) that immediately sends the same message, which is then finally received by process A. The restriction is not violated. In the second solution, the message *m2* is once again

[10]The parent of a process X, combined with the siblings of that process X are called the *environment* of process X, which X knows nothing about.

sent by process C and received by process D, which now sends a message *m2'*. That message is then received by process *Main*, which sends a message *m2* to process A. Note that in the second solution, one message was renamed to *m2'*, as messages sent by process D can be received by both processes *Main* and A. This is an example of a name clash (of message *m2*)!

In the current ToolBus, we needed only one communication to send message *m2*. Now we need at least two communications to get the same result. This effect will be referred to as *chaining*, as the single communication is 'cut up into a chain'.

The difference between the two solutions is whether process D sends the message directly to process A, or via process *Main*. In general, there are two options when chaining between two siblings: direct communication (one communication step), or communication via the parent (two communication steps). The decision can be made by the parent (process *Main* in the example) and is completely transparent to all parties involved, except for the renaming of message *m2* to *m2'*. However, such renaming will no longer be necessary when namespaces are introduced in Section 6.3. Also note that in none of the solutions it was required to change the original sending and receiving processes (processes C and A), as they still respectively send and receive message *m2*.

The restriction makes sure that communication can't go too far up or down the hierarchy in a single communication step, thereby enforcing abstraction. We have seen that this results in messages having to travel up and down the hierarchy, which increases the amount of communication in the system. However, it also allows for more control, as on each level extra actions (like logging and dependability checks) can be added. So, longer chains allow for more control, while shorter chains are better performance wise. In practice, a tradeoff will have to be made.

```
process D is
  let Pid: int
  in  create(B, Pid?) .
      create(C, Pid?) .
      /* omitted */
      ||
      ( rec-msg(m2) .
        snd-msg(m2)
      ) * delta
  endlet
```

Figure 10: Typical chaining solution T script

There is another downside to chaining. Figure 10 shows the T script for process D of the first solution from Figure 9. The chaining of one single message by one single process requires the use of the $\|$ operator and an infinite loop of receiving and sending the message. However, we need the loop only if process C can send message *m2* multiple times. When chaining lots of messages, adding these blocks of script that run in parallel becomes very tedious for the T script programmer. When messages get longer and have several parameters, things get even worse. Also, the parallelism within single processes makes everything look very complicated.

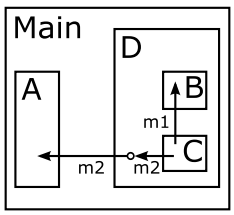
A single communication being cut up into a chain of multiple communications has another downside besides degraded performance; it may be so that the first communication step of the chain is completed, but the next one is not enabled. Obviously, this problem doesn't occur for single step communications, therefore this is a new problem that emerges due to chaining.

6.2.4 Relays

As we have seen, the advantage of chaining is more control and the biggest downside is degraded performance as the result of multiple communications. To overcome the problems of chaining, *relays* are now introduced. There are two types of relays: *exports* and *connects*. The *connects* relay will be introduced in Section 6.4.2, the *exports* relay will be introduced in the remainder of this section.

Processes can export communications (messages and notes) from the child processes to the environment, or import them in the opposite direction, by using the *exports* relay. This exporting of communications is almost identical to having the process itself receive the message and sending it on again, thereby (manually) relaying the message (as in Figure 10). The difference is that relays don't introduce extra messages as the ToolBus will follow the chain of relays to find out all processes to which it leads. All those processes may then directly communicate. Note however that they may only directly communicate the messages that were relayed.

Figure 11 shows the relay solution to our example. Process C still sends a message *m2*. It is now relayed by process D from process C to the environment of process D. Note the difference in dots, as the chaining solution has a solid dot, while the relay solution has an open dot. Since processes D and A may directly communicate (they are siblings), the relayed message can be received by process A. Both the chaining solution and the relay solution will have the same behavior, but in the case of the relay solution, there is only a single communication needed to get message *m2* from process C to process A.



(Relay solution)

```
process D is
  exports(m2)
  let Pid: int
  in  create(B, Pid?) .
      create(C, Pid?) .
      /* omitted */
  endlet
```

(T script)

Figure 11: Example of relays

When we look at the T scripts of both the chaining solution and the relay solution, we see that the relay solution doesn't have the $\|$ operator; it doesn't have the infinite loop and it doesn't have the duplication of the message (pattern).

It is therefore very easy to add such a relay. Note that the `exports(...)` keyword must immediately follow the `is` keyword. Also, there is no dot (sequential composition) operator between the `exports(...)` keyword and the expression defining the process.

This example has only a single relay, but it's also possible to have multiple relays. Just separate the message patterns by commas. It is even possible to relay messages that have parameters. See Appendix A for the full SDF syntax of T scripts. Here is another example of an exports relay:

```
exports(msg1, msg2(<int>, <str>), msg3(<int>))
```

One may wonder why there is an exports relay, but no imports relay. The reason is that both would have the same functionality and only one of them is needed. The reason that only the exports relay is included (instead of only the imports relay), is that the exports keyword clearly indicates that this relay is part of the external interface of a process. See Section 7.2 for more information on interfaces and section 6.4.3 for a more detailed discussion on imports vs. exports.

We have seen that relays solve the performance problems of chaining, the developer and code complexity problems, as well as the 'next step not being enabled' problems. However, chaining is still possible, as it allows for extra control when needed.

6.2.5 Summary

To summarize, a (direct) communication is only possible if the following requirements are met:

- The messages match. This is checked by using standard ATerm pattern matching.
- The communication restriction must not be violated. A process may now only directly communicate with its parent, its siblings and its children (all three because of the communication restriction), as well as all the processes it's connected to via relays (also called *relay chains*).

One may still wonder if it wouldn't be better to allow multiple top level processes. It is now possible to better motivate that choice. Assume we do indeed allow multiple top level processes. Then we have multiple hierarchies (each with its own top level process) and we want to connect the hierarchies in some way (to allow communication between them). We could allow the top level processes to communicate directly, as if they are siblings. Then it nicely conforms with the communication restriction. However, if we simply just create a new top level process with a unique name and let it instantiate all the 'original' top level processes, then they are automatically siblings of each other. It is true that it would be a little bit of work to create the new top level process definition, but it is very easy and it won't take long. Also, the 'new' top level process can exercise

more control over the communication between the 'original' top level processes. Furthermore, this way, there are no exceptions, while in the case of multiple top level processes, the top level processes are considered to be siblings, which is a sort of an exception to the rule (as they don't have parents). Finally, this way we only have to provide the ToolBus with the name of the single top level process, where in the case of multiple ones we have to indicate in some way the names of all those top level processes. That could be done by reintroducing the `toolbus(...)` keyword, but this would once again introduce some static qualities that we just got rid of.

6.3 Namespaces

One of the problems introduced in Section 5.1 was the problem of name clashes (of messages). To solve that problem, namespaces will now be introduced. Note that namespaces will be added on top of the ToolBus system with hierarchical processes and the communication restriction as described in Sections 6.1 and 6.2.

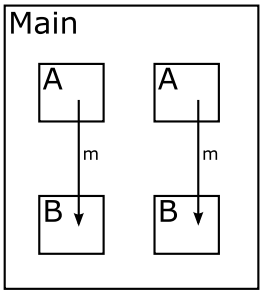
The idea of namespaces is that messages can be sent within a sort of 'group' (called a *namespace*). Messages sent in different namespaces are then considered to be different messages and won't match. Therefore, messages in different namespaces won't clash. So, besides solving name clashes, namespaces are also a form of abstraction. However, abstraction by means of the restriction is *enforced* abstraction, while abstraction by means of namespaces is *optional*.

6.3.1 An example

Let's start with an example of a name clash. Figure 12 shows the intended system, the T script for that system and the actual system that the T script represents. It is an abstract example in the sense that the system doesn't have a goal/meaning. It may however be useful to think about it this way: process A and B together complete some task and this task has to be performed twice at the same time (in parallel). The obvious problem is that there is no way to distinguish the two instances of process A (or the two instances of process B). Therefore, the messages m sent by either of the processes A may be received by either of the processes B and there is no way to tell which one. Note that this is similar to the example of the name clash from Section 5.1.

6.3.2 Instantiating processes in namespaces

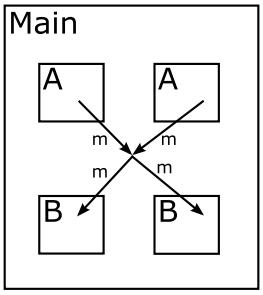
The first place that namespaces will pop up, is in the instantiation of processes, as processes may now be instantiated within a namespace. In Figure 13 we can see what that looks like. The figure (Solution 1) shows that a process A and a process B are instantiated in a namespace x (depicted as a (red) dotted box), while the other processes A and B are instantiated in a namespace y. This solves the problem of name clashes, as messages in namespace x can't clash with messages in namespace y. They don't clash, simply because they don't match, as only messages within the same namespace can match.



(Intended system)

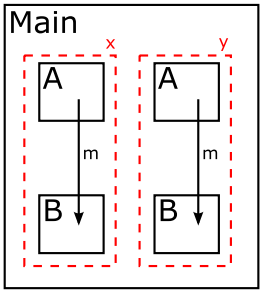
```
process Main is
  let Pid: int
  in  create(A, Pid?) .
      create(A, Pid?) .
      create(B, Pid?) .
      create(B, Pid?)
  endlet

process A is
  snd-msg(m)

process B is
  rec-msg(m)
```

(T script)



(Actual system)

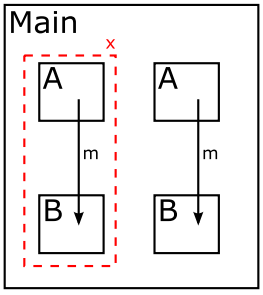
Figure 12: Example of a system with name clashes



(Solution 1)

```
process Main is
  let Pid: int
  in  create(x/A, Pid?) .
      create(x/B, Pid?) .
      create(y/A, Pid?) .
      create(y/B, Pid?)
  endlet

process A is
  snd-msg(m)

process B is
  rec-msg(m)
```

(T script for solution 1)



(Solution 2)

Figure 13: Example of namespaces solving name clashes

Figure 13 also shows a second solution (Solution 2), in which only two processes are instantiated within namespace x. The other two are not instantiated within a namespace. Processes that are not instantiated within a namespace are also said to be 'instantiated within the empty namespace'. That solution also solves the name clashes, as messages in namespace x can't clash with messages outside of that namespace.

In Solution 1, all processes were instantiated within a namespace. In Solution 2, only some were. In general, namespaces are optional, not required. Furthermore, as we have seen, multiple processes may be instantiated within the same namespace. The complete freedom in using namespaces allows for great freedom in solving name clashes.

6.3.3 Absolute vs. relative namespaces

All namespaces are relative. They are relative to the namespace that the parent process was created in. Let's look at an example. Figure 14 shows a system in which the process *Main* instantiates a process A in namespace x/y. The namespace x/y is the namespace y inside the namespace x. The process A in turn instantiates the process B in namespace *abc*. Remember that all namespaces are relative. Therefore, the absolute namespace that process B lives in, is namespace $x/y/abc$.

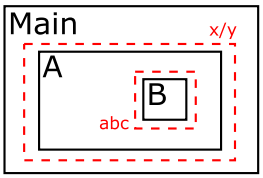


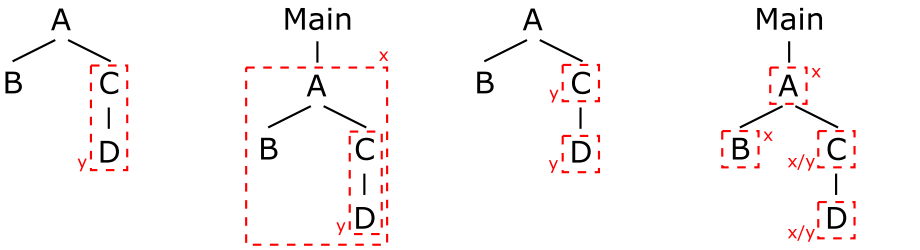
Figure 14: Example of relative namespaces

The benefit of relative namespaces is that they form a hierarchy. Any (parent) process can decide to put the entire subtree rooted at one of its children in a namespace, simply by instantiating that child process (which is the top level process of such a subtree) in that namespace. This way, an entire subtree of processes can be put in a namespace that the (parent) process knows will never clash with any other messages of that process.

With absolute namespaces, one basically just prefixes the processes with some constant, which is less powerful. It would then be much more complicated to put an entire subtree in a different namespace, as *all* processes in that subtree would have to be prefixed with the same constant. Not only would that be a lot of work, it would also involve changing the definitions of those processes, unlike with relative namespaces.

Figure 15 shows an example of this. Process A is the top level process of a component. In the relative version (see the left one in the figure), process C is created in relative namespace y. This also means that process D is automatically instantiated in that namespace as well. Now we put the component in a new

system (see the second one from the left in the figure). We want to put the component in namespace x. To do that, we only need to instantiate process A (which is the top level process of the component) in namespace x. As for the absolute version of the component, both processes C and D need to be explicitly created in namespace y, as namespaces are absolute (see the third one from the left in the figure). When we want to use the component in a new system in namespace x, each and every one of the processes needs to be instantiated in namespace x explicitly (see the right one in the figure)! The definitions of all processes (except the leaf processes, that is processes B and D) need to be modified. It should now be clear that with relative namespaces this was much easier to accomplish.



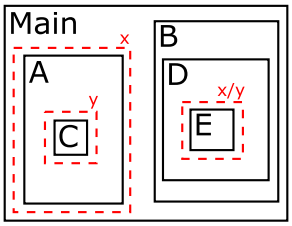
(Relative component) (Relative system) (Absolute component) (Absolute system)

Figure 15: Absolute vs. relative namespaces

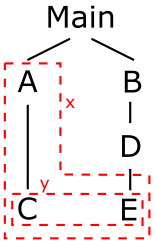
The (relative) namespaces are relative to the process hierarchy, in the sense that the (relative) namespace that a process is instantiated in, is relative to the absolute namespace of its parent process. Figure 16 shows a system overview as well as both the process hierarchy and the namespace hierarchy of that system. From that figure it should be clear that the namespace hierarchy is independent of the process hierarchy. A consequence of this independence is the complete freedom in using namespaces. The process hierarchy was chosen as support structure for relative namespaces because it was already in place and because it fits nicely. You may wonder if the fact that processes C and E live in the same absolute namespace gives rise to name clashes. However, this is not the case, since the communication restriction applies and they are not allowed to directly communicate.

6.3.4 Communication actions and namespaces

So far we have only seen namespaces pop up when instantiating processes. However, messages and notes can also be sent and received in namespaces. Figure 17 shows a third solution to the name clash problem of Figure 12. In this solution, one process A is instantiated in a namespace x and one process B is instantiated in a namespace y. The message m sent by process A in namespace x, is received by process *Main* (the parent of process A). It is then sent (by *Main*) to process B in namespace y. Note how the communication actions in process *Main* have their ATerms prefixed with namespaces. See Appendix A for the



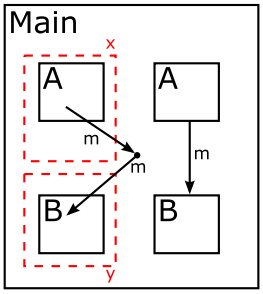
(Overview of some system)



(Both hierarchies)

Figure 16: Example of the independence of the namespace hierarchy

full SDF syntax of T scripts. Also note that in none of the three solutions the definitions of processes A and B needed to be modified!



(Solution 3)

```
process Main is
  let Pid: int
  in  create(x/A, Pid?) .
      create(y/B, Pid?) .
      create(A, Pid?) .
      create(B, Pid?)
      ||
      ( rec-msg(x/m) .
        snd-msg(y/m)
      ) * delta
  endlet

process A is
  snd-msg(m)

process B is
  rec-msg(m)
```

(T script for solution 3)

Figure 17: Example of sending/receiving messages in namespaces

Note that we can now solve the problem of 'Chaining solution 2' (Figure 9), where we had to rename message *m2* to *m2'*. Figure 18 shows the new solution. Process A is created in namespace x and process D is created in namespace y. Since they are now created in different namespaces, process D can just send message m as usual. Process *Main* can then receive it (in namespace y) and send it on to process A (in namespace x).

6.3.5 Some additional examples

Figure 19 shows another example of a system (System 1) that uses namespaces. Process *Main* instantiates process A in the empty namespace and process B in namespace x. In process A, message *m1* is sent in namespace x, message *m2* is sent in the empty namespace and message *m3* is sent in namespace y. In process B, message *m1* is received in the empty namespace, while messages *m2* and *m3* are received in namespace z.

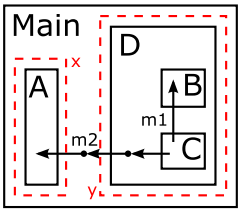
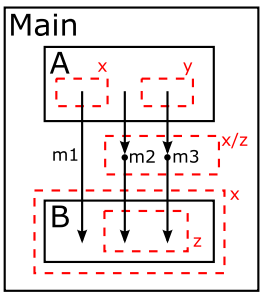


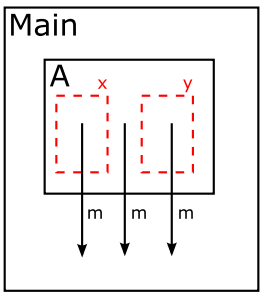
Figure 18: No more renaming necessary



(System 1)

```
process Main is
  let Pid: int
  in  create(A, Pid?) .
      create(x/B, Pid?) .
      ( rec-msg(m2) .
        snd-msg(x/z/m2)
      +
        rec-msg(y/m3) .
        snd-msg(x/z/m3)
      )
  endlet

process A is
  snd-msg(x/m1) .
  snd-msg(m2) .
  snd-msg(y/m3)

process B is
  rec-msg(m1) .
  rec-msg(z/m2) .
  rec-msg(z/m3)
```

(T script for system 1)



(System 2)

Figure 19: Examples of namespaces

Message *m1* is sent by process A in namespace x. It is received by process B that is instantiated in the namespace x. Both communication actions operate in absolute namespace x, therefore they may communicate.

Message *m2* is sent by process A in the empty namespace. It is received by process *Main*. It is then sent (by process *Main*) to process B in the (absolute) namespace x/z. In process B the message *m2* is received in absolute namespace x/z, since process B was instantiated in namespace x and the process receives the message in relative namespace z.

Message *m3* is similar to message *m2*, except that it is first sent in namespace y and therefore it is received by process *Main* in that namespace as well.

Note that it is impossible for process B to (directly) communicate with any message outside of namespace x[11], since process B was instantiated in namespace x. Any namespace specified with a messages in process B (like for instance the namespace z of message *m2*) is relative to the absolute namespace of that process (which is namespace x).

We have already seen that processes may be instantiated in any namespace, or in no namespace at all. The same is true for messages and notes; namespaces are optional and there is complete freedom in using them.

Figure 19 also shows a second system (System 2). In that system we see that process A sends the same message m three times. However, since they are all sent in different namespaces (that is, namespace x, namespace y and the empty namespace), they can now be differentiated!

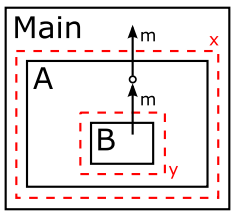
6.4 Chaining and relays revisited

In this section the topics of chaining and relays are revisited, since the addition of namespaces has a significant impact on them.

6.4.1 Relays with namespaces

Let's start with an example of some relays with namespaces (Figure 20). Process B sends a message m. Process A exports (relays) that message to its environment in namespace y, since process B was created in that namespace. Finally, process *Main*, which is part of the environment of process B, will receive the message in namespace x/y, since process A is instantiated in namespace x and process A exported the message in (relative) namespace y. Note that, since a relay is used, there is only a single communication. Also note that the messages in the relays may now be prefixed with (relative) namespaces.

[11] This will change in Section 6.4.2.



(System)

```
process Main is
  let Pid: int
  in  create(x/A, Pid?) .
      rec-msg(x/y/m)
  endlet

process A is
  exports(y/m)
  let Pid: int
  in  create(y/B, Pid?)
  endlet

process B is
  snd-msg(m)
```

(T script)

Figure 20: Example of relays with namespaces

6.4.2 Connects relays

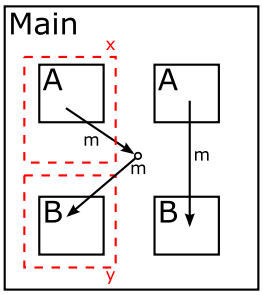
Now that we have namespaces, a new type of chaining problem manifests itself. In Figure 17 we solved a name clash. This resulted in a single communication being split up into a chain consisting of two communication actions. Earlier we fixed the problem of multiple communications by using (exports) relays. However, the processes A and B are siblings. Therefore, in this case, an exports relay won't help us. To solve the problem of two siblings instantiated in different namespaces not being able to communicate directly, the *connects* relay will now be introduced.

Processes can relay communications (messages and notes) between their child processes by using the *connects* relay. This relaying of communications (by using the *connects* relay) is similar to the (parent) process receiving a message from one of its children and then sending (thereby manually relaying) it to one of its other children (as in Figure 17). Once again, relays result in single communications, instead of a chain of communications.

The introduction of the *connects* relay in itself is not enough. Let's look at the *connects* relay version (Figure 21) of Figure 17. Process *Main* relays (connects) message m from namespace x to namespace y.

All relays (thus, connects as well as exports) may have the optional `in ...` part. It can be used to relay messages from a source namespace to a target namespace (both relative). The namespace before the message is the *source* namespace. The namespace after the `in` keyword is the *target* namespace. In case no target namespace is specified, it is equal to the source namespace. Note that siblings in the same (absolute) namespace can already directly communicate. Therefore, it makes no sense not to use a target namespace for connects relays, since if you don't, the messages are relayed within the same namespaces.

It is also possible to relay messages from a (relative) namespace to the empty (relative) namespaces by using slash (/) as the (relative) target namespace. Figure 22 shows the same system as in Figure 20, but the T script is different (the relay is different). Process B still sends message m. It is still relayed



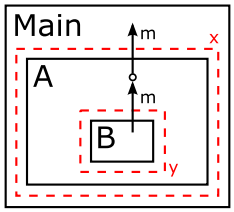
(System with connects relay)

```
process Main is
  connects(x/m in y)
  let Pid: int
  in  create(x/A, Pid?) .
      create(y/B, Pid?) .
      create(A, Pid?) .
      create(B, Pid?)
  endlet

process A is
  snd-msg(m)

process B is
  rec-msg(m)
```

(T script for the system)

Figure 21: Example of a connects relay

(exported) by process *A* from namespace *y* to the environment. However, it is exported from (relative) namespace *y* to the empty (relative) namespace. It is then finally received by process *Main* in namespace *x*, since process *A* is instantiated in that namespace and the message was exported by process *A* in the empty relative namespace. Note that namespace *x/* is just written as namespace *x*, since leading and trailing slashes are always omitted.



(System)

```
process Main is
  let Pid: int
  in  create(x/A, Pid?) .
      rec-msg(x/m)
  endlet

process A is
  exports(y/m in /)
  let Pid: int
  in  create(y/B, Pid?)
  endlet

process B is
  snd-msg(m)
```

(T script)

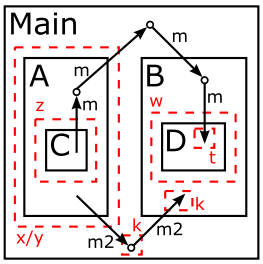
Figure 22: Example of relaying to empty namespace

Just as with the *exports* relays, the *connects* relays can be used to relay multiple messages. Also the *connects* relay should be located after the `is` keyword and before the expression defining the process. If both *exports* and *connects* relays are present in a process, they may be placed in any order. Only at most one `exports(...)` keyword and at most one `connects(...)` keyword are allowed per process (they may however contain multiple comma-separated relays each). See Appendix A for the full SDF syntax of T scripts.

6.4.3 Another example of relays

Figure 23 shows another example. Process C sends a message m. It is relayed (exported) by process A, after which it is relayed (connected) by process *Main* from the $x/y/z$ namespace to the empty namespace. Then process B imports it from the empty namespace to namespace w/t (actually, it exports it from namespace w/t to the empty namespace, but as we will see later on, that is the same!). Finally, process D receives it in (relative) namespace t.

Also, process A sends a message *m2*. It is relayed (connected) by process *Main* from namespace x/y to namespace k. Finally, this message is received by process B in namespace k.



(Example system)

```
process Main is
  connects(x/y/z/m in /,
           x/y/m2 in k)
  let Pid: int
  in  create(x/y/A, Pid?) .
      create(B, Pid?)
  endlet

process A is
  exports(z/m)
  let Pid: int
  in  create(z/C, Pid?) .
      snd-msg(m2)
  endlet
```

(T script)

```
process B is
  exports(w/t/m in /)
  let Pid: int
  in  create(w/D, Pid?) .
      rec-msg(k/m2)
  endlet

process C is
  snd-msg(m)

process D is
  rec-msg(t/m)
```

(T script)

Figure 23: Another example of relays

6.4.4 Direction of relays

For all relays, there is a *source* namespace and a *target* namespace. The *source* namespace is the one before the message ATerm. The *target* namespace is the one after the `in` keyword. If no target namespace is specified, it is equal to the source namespace.

In Section 6.2.4 it was mentioned that the *exports* keyword is used for both exporting as well as importing. The decision was made to only include *exports*, because it clearly indicates that such relays are part of the external interface of a process. In Figure 23 we saw an example of both an import of a message as well as an export of a message.

For *exports* relays, the *source* namespace is always related to the child processes and the *target* namespace is always related to the environment. When exporting, we go from source namespace to target namespace (see process A in the example). It is also possible to look at it from the opposite direction; to look at it as an import. In that case the (*exports*) relay *imports* the message from the target namespace (still related the environment) to the source namespace (still related to the child processes). So, when importing, we go from target namespace to source namespace (see process B in the example). Note that im-

porting and exporting are the same thing, only the direction is different. The *exports* keyword has an exports related syntax, giving rise to source and target definitions from an exports view. This is the reason that when looking at it from an imports view, the source and target seem to be switched. Actually, assuming we indeed had an *imports* relay, then it would have been exactly the same as the *exports* relay, except for the swapped *source* and *target* namespaces. In that case, both *imports* and *exports* relays would have been *imports* as well as *exports*, which is the reason only one of them was included.

With *connects* relays, we relay between siblings. In this case the *source* namespace corresponds to one of the children (of the process that relays) and the *target* namespace corresponds to one of the other children of that same process.

6.4.5 Note on relay targets

For both *exports* and *connects* relays, it's possible to relay messages from one namespace to another (by using `in ...`). It is however not possible to change the message pattern. This was done deliberately, since allowing changes in message patterns makes ToolBus systems very complex. Not only would they be harder to understand, it would also be much more difficult to implement such relays (as it would require complex renaming machinery). Furthermore, performance could degrade significantly. Note however that using chaining, such 'renaming' is still possible. Hopefully, such changes will occur only sporadically and therefore a small performance penalty is acceptable. This is actually expected to be true. See also Section 8.2.

6.5 Summary

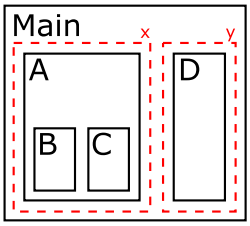
Namespaces were introduced on top of the ToolBus with hierarchical processes and the communication restriction. In a ToolBus with both hierarchical processes, the communication restriction and namespaces (including relays), a (direct) communication can only occur if the following three conditions are met:

- The messages match. This is checked by using standard ATerm pattern matching.
- The namespaces in which the messages are sent and received match (possibly via relays).
- The communication restriction must not be violated. A process may now only directly communicate with its parent, its siblings and its children (all three because of the communication restriction), as well as all the processes it's connected to via relays (also called relay chains).

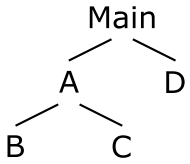
In such a ToolBus system there is enforced abstraction by means of the restriction as well as optional abstraction by using namespaces.

6.6 Example of direct communication

With the addition of namespaces and relays it becomes a bit harder to see what *direct communications* (also called *single step communications*) are possible in a system. Figure 24 shows an (abstract) example system that should demonstrate this. All communications are omitted in this figure, as we are only interested in *possible* (direct) communications. Table 3 shows which processes may communicate which messages with which other processes in a single step, as well as the relationship between those processes that allows them to do so.



(Example system)



(System hierarchy)

```
process Main is
  connects(x/msg1 in y)
  let Pid: int
  in  create(x/A, Pid?) .
      create(y/D, Pid?) .
      /* omitted */
  endlet

process A is
  exports(msg2)
  let Pid: int
  in  create(B, Pid?) .
      create(C, Pid?) .
      /* omitted */
  endlet

process B is
  /* omitted */

process C is
  /* omitted */

process D is
  /* omitted */
```

(T script)

Figure 24: Example of direct communication

Process *Main* may (directly) communicate any message with both its children, processes A and D. Since process A relays message *msg2*, process *Main* may also communicate that message with both processes B and C.

Process A may communicate any message with its parent and its two children. It may also directly communicate any message with its sibling (process D). However, they are both instantiated in different namespaces, so direct communication is impossible. Except for message *msg1* that is, since that message is relayed by process *Main*.

Both processes B and C may directly communicate any message with their common parent as well as each other (they're siblings). They may also directly communicate message *msg2* with process *Main*, since it is relayed by process A.

Finally, process D may directly communicate any message with its parent (process *Main*) as well as its sibling (process A). However, once again only message *msg1* can be directly communicated as they are both in different namespaces and only that message is relayed by process *Main*.

Process 1	Process 2	Relationship	Messages
Main	A	Child	Any
	B	Relay via A	msg2
	C	Relay via A	msg2
	D	Child	Any
A	Main	Parent	Any
	B	Child	Any
	C	Child	Any
	D	Sibling	Any/None
	D	Relay via Main	msg1
B	Main	Relay via A	msg2
	A	Parent	Any
	C	Sibling	Any
C	Main	Relay via A	msg2
	A	Parent	Any
	B	Sibling	Any
D	Main	Parent	Any
	A	Sibling	Any/None
	A	Relay via Main	msg1

Table 3: Overview of possible direct communication in example system

Obviously, any direct communications that are listed as possible are still subject to ATerm matching as well as (absolute) namespaces matching.

6.7 Syntax considerations

The syntax as proposed in this section is merely prototype syntax. For instance, exports and connects relays could also be put directly before the `is` keyword instead of directly after it. Also, instead of `connects x/m in y` we could use a syntax like `connects m from x to y`. In general, the syntax is just a proposal. See Appendix A for the full (proposed) SDF syntax of T scripts.

6.8 Orthogonality of solutions

Namespace were introduced on top of the ToolBus with hierarchical processes and the communication restriction. This makes you wonder if the concepts of hierarchy and namespaces are orthogonal or not.

If namespaces would have been introduced as a completely separate concept on top of the current ToolBus (without hierarchical processes), all processes would have been able to directly communicate with each other. In such case, communication is possible if both the messages match (standard ATerm pattern matching) and the namespaces match. Namespaces would then be the only form of (optional!) abstraction present. Note that the absence of a hierarchical structure would also mean that *exports* relays are useless. As for *connects* relays, they could still be used. However, it would be a bit of a puzzle where to define

them, as there is no 'parent' process.

It should be clear that it is possible to use namespaces without having a hierarchical structure. Therefore, both concepts are orthogonal. Only when we combine them, we get the problem of chaining. Relays are a solution to the problems of chaining and therefore only really make sense when we combine the hierarchical structure with namespaces. So, the concepts of hierarchy and namespaces are in principle orthogonal, but in the total solution a relation between them definitely exists.

6.9 Summary

The `toolbus(...)` construct is no longer used, instead all processes are instantiated using the `create(...)` keyword. Also, we keep track of the resulting hierarchical process structure. Because of the communication restriction, which sole purpose is to enforce abstraction, processes may only directly communicate with their parent, their siblings and their children. A consequence of this is that communications may have to be 'cut up into chains of communications' in order not to violate the restriction. This is called the chaining effect. Some of the problems with chaining include degraded performance and more complicated T scripts. In order to allow processes that may not directly communicate (because of the communication restriction or namespace restrictions) to do so anyway, relays are introduced. The first type of relay is the exports relay, which is introduced to get around the problems of chaining. Using exports relays, processes may allow their environment and their children to directly communicate, thereby relaxing the communication restriction locally. To solve name clashes the concept of (relative) namespaces is introduced. Processes may now be instantiated in namespaces and messages may be sent and received in them. To allow siblings living in different namespaces to directly communicate, a second type of relay (the connects relay) is introduced, which relays messages between siblings from one namespace to another. The namespace structure is hierarchical, just like the process structure and while both structures are related, they are not the same.

7 Requirements revisited

In this section the solution, as presented in Section 6, will be discussed with respect to the requirements as listed in Section 5.2. Also, in Section 7.9 a consequence of the solution is discussed. Although it doesn't discuss a requirement, it fits best here.

7.1 Hierarchy (R1) and Abstraction (R2)

It should be clear that processes form a hierarchical structure. Abstraction is based on restricting the possible communications and is enforced. Also, namespaces provide a limited form of (optional) abstraction. Note that namespaces have a hierarchical structure as well. The two hierarchies are related, as processes can be instantiated within a namespace, but they are certainly not identical.

7.2 Interfaces (R3)

Requirement R3 demands the existence of clearly defined interfaces. So, what do interfaces of processes look like? We will see how we can extract the interface of a process from its definition. However, we will also see that interfaces in their current form are far from optimal.

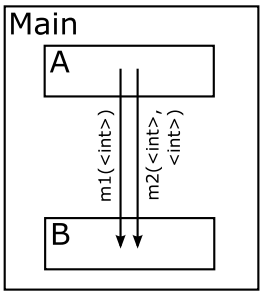
7.2.1 Definition and examples

An interface of a process is just a list of all the communications extracted from the definition of that process, combined with all the exports of that process. Figure 25 shows the interfaces of all processes of the system from Figure 23. Note that process *Main* is not included in the figure, since its interface is empty. Also note that *connects* relays are not included as they relay messages between child processes and are therefore not part of the *external* interface of a process.

`exports(z/m)` `snd-msg(m2)`	`exports(w/t/m in /)` `rec-msg(k/m2)`	`snd-msg(m)`	`rec-msg(t/m)`
(A)	(B)	(C)	(D)

Figure 25: Examples of interfaces

In Figure 26 we see another system, which has messages with variables. The interfaces are still just lists of all the communications extracted from the definition of the processes (process *Main* has an empty list of communications), combined with all *exports* relays (none in this example). Note that the variables have been replaced by their types.



(System)

```
process Main is
  let Pid: int
  in  create(A, Pid?) .
      create(B, Pid?)
  endlet

process A is
  let I: int
  in  snd-msg(m1(5)) .
      snd-msg(m2(5, I?))
  endlet

process B is
  let I: int, J: int
  in  rec-msg(m1(I?)) .
      rec-msg(m2(J?, I))
  endlet
```

(T-scripts)

```
[interface process A]
snd-msg(m1(5)) .
snd-msg(m2(5, <int>?))

[interface process B]
rec-msg(m1(<int>?))
rec-msg(m2(<int>?, <int>))
```

(Interfaces)

Figure 26: More examples of interfaces

From the interface of a process we can see exactly which messages it can send and receive, as well as the namespaces they will be sent and received in. We can also see if the process sends variable contents (for instance: `<int>`) or receives data in variables (for instance: `<int>?`).

7.2.2 Internal vs. external communication

We will now go into the fact that interfaces, as just defined, are not interfaces in the traditional sense, since they also contain internal communications.

Figure 27 shows (on the left) the interface of process D from Figure 9 (Chaining solution 1). The interface contains all messages sent and received by that process. This includes the internal communication (with its children) as well as external communication (with the environment). Just by looking at the interface, it's impossible to see what communications are internal and what communications are external.

From the original figure showing the system, we can see that the receive action is meant to be internal to that process (received from child process C) and that the send action is meant to be external (to sibling A). However, as stated, we cannot distinguish that from the interface.

Figure 27 also shows that same system with added namespaces (in the middle) and the interface of process D in that case (on the right). The send action (in namespace e) is now definitely external; the child processes are instantiated in different namespaces (b and c) and there are no *connects* relays in process D, which means that messages from the child processes can never match any of the messages in namespace e. The receive action (in namespace c) is now most likely internal, as it matches the namespace that one of the child processes was created in. However, the parent process (process *Main*) could send an *m2* message (in the d/c namespace) and it would match as well.

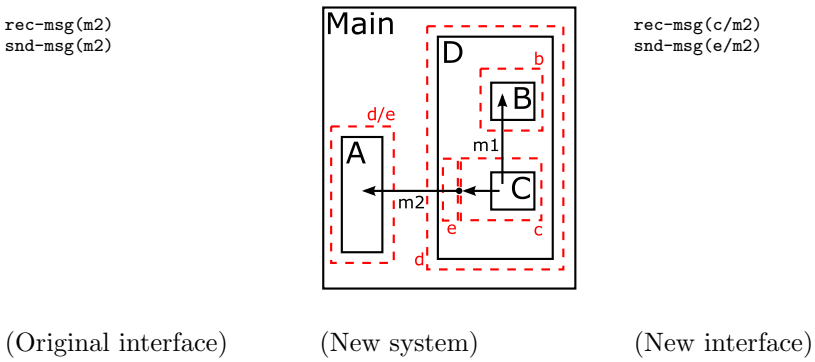


Figure 27: Example of internal vs. external communication

So, by looking at the process definitions we can sometimes say something about what communication is internal and what communication is external. However, none of it can be determined from the interface alone! What we really want, is to be able to get only the *external* interface of a process, as that is all we are interested in. After all, the internal communications should be abstracted away. The fact that this approach to interfaces doesn't allow us to make the distinction between internal and external communications could be considered the main disadvantage of the solution presented in Section 6. A proposal for solving this problem is described in Section 11.7.

7.2.3 Benefit of interfaces

After reading the previous section you may think that interfaces (in their current form) are completely useless. However, this is not the case.

Assume one (randomly) picks a single process in the process tree (process hierarchy) of a ToolBus system. That process is then the root of a subtree of the process hierarchy, which includes the process itself as well as all of its children, the children of its children, the children of the children of its children, etc. Since processes can only directly communicate with their parent, children and siblings, none of the processes in the subtree (except for the root) can (directly) communicate with any other process outside of the subtree (the environment). An exception is when the root process relays messages from its children to the environment (and vice versa). However, all such relays between the environment and processes in the subtree go via the root process. This means that, because of the enforced abstraction (by means of the communication restriction), the interface of such a root process defines the external interface of the entire subtree! This is one of the biggest benefits of the enforced abstraction.

So, the interface of the root process of a subtree in the process tree defines the external interface of that entire subtree. However, interfaces (in their current form) contain some internal messages as well. But still, the interface of a process (in its current form) *contains* the (ideal external) interface of the entire subtree. Therefore, interfaces (in their current form) are useful to some degree, but not

nearly as useful as they would be if they only contained the *external* interface. Essentially, it is better to have some form of interfaces than no interfaces at all.

7.2.4 Summary

It is possible to extract an 'interface' of a process from its definition. These interfaces consists of a list of all the communication actions from the definition of the process, combined with all its *exports* relays. We have seen that it is impossible to determine (from the interface alone) if communication is internal or external; the 'interfaces' contain internal details. However, the interface of a process defines the interface of the entire subtree rooted at that process.

7.3 Evolution and reuse (R4)

With the extensions in place, it should be much easier to replace a part of a system by an equivalent part. We just have to make sure that the interfaces of both processes are the same. Or, to be more precise, the new process should have at least the interface of the replaced process. Then we just change the instantiation (within the definition of the parent of the replaced process) from the old to the new process. This way we don't just replace a single process, but an entire subtree of the hierarchy! We no longer have to manually check which (possibly huge) collection of processes we have to remove. However, there are still things that can go wrong. For instance, the new process could have the same interface, but a completely different behavior. This is something that developers must check manually.

Also, additional messages may be added to the interface of a process (for instance as an alternative composition on the highest level of the process). As long as the rest of the interface remains the same, the locations where the process was already included can still count on the existence of the original messages (the original interface).

Replacing and extending systems becomes easier, thus making evolution of systems much easier to manage. Also, reuse of processes is encouraged. Since processes are completely unaware of where they will be instantiated (they have no knowledge of their environment), they can be included wherever needed. And because of the fact that interfaces of root processes of subtrees define the external behavior of the entire subtree, we can reuse entire subtrees of processes (which could be seen as the equivalent to components in many programming languages), simply by instantiating that root process.

7.4 Semantics (R5) and formal foundation (R7)

It is possible to translate new systems to old ones (without namespaces). See Section 9.1 for more details on the translation. While the extensions are certainly useful, the existence of such a translation proves that they don't add additional expressional power to the ToolBus.

The introduction of all the new concepts obviously changes the semantics of the ToolBus. The semantics of one of the earlier versions of the ToolBus are given by means of Structured Operational Semantics (SOS) in [9]. Unfortunately, that document is already more than ten years old. At this point there is no complete set of semantic rules for the new version of the ToolBus. However, it should be possible to update the semantics. This would entail the introduction of some new functions, for instance one from each process to its parent. The most work would have to go into the rules for communication, as the communication restriction, namespaces and relays would have to be incorporated. So, once the semantics rules have been updated, the ToolBus will once again have a strong formal foundation.

7.5 Backwards compatibility (R6)

How does the proposed solution affect existing systems? Assume we have an existing system that we want to run using the new ToolBus system. The `toolbus(...)` keywords are no longer used. They will have to be removed, although the implementation of the new ToolBus could simply ignore them. Instead of those `toolbus(...)` keywords a single parent process (which could be called process *Main*) will have to be added that creates (instantiates) all the other processes that were previously instantiated by means of the `toolbus(...)` keywords. Since then all processes are children of the single top level process, they are all siblings of each other. This means that they are allowed (by the communication restriction) to directly communicate, just as in the current ToolBus.

It is very easy to automate such a translation for existing system to the new format. The ToolBus could detect when an old T script file is used. It could then display a warning indicating the T script should be converted to the new format. Alternatively it could even do that automatically (and even silently).

Existing ToolBus systems don't use namespaces or relays, so that is no problem. However, to take full advantage of the new features, existing systems may need significant rewriting and restructuring.

7.6 Performance (R8)

The communication restriction makes it easier to determine which processes a process may communicate with, as it localizes the analysis. However, we also have relays. That makes the analysis much more complex and time consuming. Furthermore, the increase in communication as a result of chaining may degrade the performance. However, the only way to know how the new ToolBus performs is by actually implementing it and performing tests on it. See also, Sections 10.1 and 11.1.

7.7 Name clashes (R9)

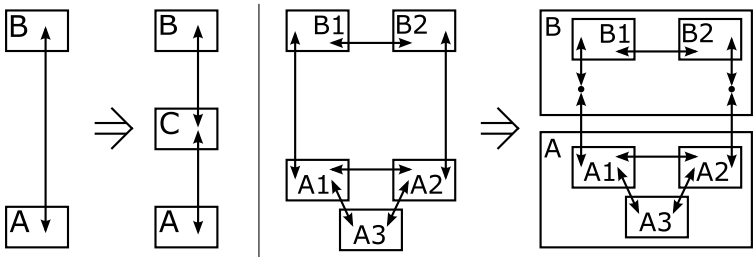
Namespaces are introduced to solve the name clashes. They provide a lot of freedom in doing so.

7.8 Dependability (R10)

One of the requirements is that all extensions should somehow make it easier to implement dependability features later on. The following two examples should show that this is indeed so. See Section 11.10 for future work on dependability.

7.8.1 Example 1

Figure 28 shows a system (System 1) consisting of two processes (A and B). Assume we know that process B may crash; the process could for instance communicate with a tool that may crash, get stuck in an infinite loop or suffer from deadlock. Also assume that we wish to make sure the entire system is dependable. To that end, we introduce a new process (process C), which interfaces between the existing two processes. Process C will monitor process B and restart it if necessary. This way, process A (and indeed, the whole system) can just continue to function, even if somehow process B crashes. Note that it is not part of this project to figure out how to monitor or restart a process. This example only just demonstrates that by adding a monitor process, we can prevent the system from crashing if a single process crashes.



(System 1) (System 2)

Figure 28: Examples of dependability

7.8.2 Example 2

Figure 28 shows another system (System 2), in which we see a subsystem A consisting of three processes. They communicate with each other and two of them communicate with the environment (subsystem B). Now, assume that the processes in subsystem B can crash. Also assume that we wish to make sure the entire system is dependable. Then, first we put all processes belonging to a subsystem inside a new process. That way their internal details are hidden from the outside. This gives us two new processes (A and B). Both act as interfacing

processes, similar to process C in the first example. All communication between processes in subsystem B and its environment are rerouted[12] through process B, effectively isolating subsystem B from the rest of the system. Isolating (a part of) a system and controlling all external interactions is called *sandboxing*. Process B will monitor all processes in subsystem B and restart them if needed. This way, if any of the processes in subsystem B crashes, process B will correct the situation. The rest of the system is completely unaware of this.

7.9 Analysis of matching communication actions

It has always been possible to check if for every *snd-msg* action there is a corresponding *rec-msg* action and vice versa. In the current ToolBus system every process may communicate with every other process. Therefore, in the analysis, for each process we have to check all other processes. In the new ToolBus, because of the communication restriction, the analysis becomes much more local. Obviously, we also have relays, which make the analysis a bit more complicated, but still we don't have to check all other processes for every process as in the current situation. The ToolBus could (optionally) give warnings for all messages that don't have a counterpart, making it possible to detect (some) deadlocks more easily. There are two methods for performing such analysis, *dynamic* checking and *static* checking.

7.9.1 Dynamic checking

Dynamic checking (at runtime) is quite difficult as some processes may not yet have been instantiated or may already have terminated. However, it is possible to check if a *snd-msg* action has more than one *rec-msg* partner in the current runtime configuration of the system. Such a situation indicates that the message may be received by either of the *rec-msg* actions and there is no way to tell which one. This could lead to unwanted behavior. Therefore, the ToolBus could give a runtime warning if such situations occur. The reverse situation, a *rec-msg* with multiple corresponding *snd-msg* actions is no problem, since for instance an error component could receive error messages from multiple sources.

7.9.2 Static checking

Let's take a look at Figure 19. Message *m3* sent by process *Main* in namespace *x/z*, matches message *m3* received in namespace *z* by process *B*, which is instantiated by process *Main* in namespace *x*.

In general, we could check for each message and note that is sent or received, whether there is a matching action, possibly via relays. It is also possible to check if there are multiple *rec-msg* actions for *snd-msg* actions, like with the dynamic check. However, if we check it statically, there is no guarantee that the

[12]This is also a good example of why, even though we have relays, chaining can still be useful.

processes involved will be instantiated and running at the same time. That is, unless we actually check that, which will most likely be rather difficult.

8 Validation

In this section some validation of the solution presented in Sections 6 and 7 will be performed. This is done by zooming in on a small part of the ASF+SDF Meta-Environment[13] to see how it could look like in the new ToolBus. Also, the compiler system example of Section 3.1 is revisited to see how it can benefit from the changes and additions.

8.1 The MouseClicked scenario

Figure 29 shows the MouseClicked scenario (the MouseClicked process and its immediate environment) of the ASF+SDF Meta-Environment as it currently is. All details irrelevant to the scenario have been omitted.

When process *EditorPlugin* receives an event (indicating the user has clicked on the editor with the mouse) from its corresponding tool, it creates an *OffsetEvent* process. This process sends a *te-mouse-click-at-offset* message. Depending on which editor is active, an *EditTerm* process, an *EditEquation* process or an *EditSyntax* process is active. Those processes contain a loop that in turn consists of an alternative composition. One of the alternatives is a process call that starts process *MouseClicked*. If a *te-mouse-click-at-offset* message has been sent, that process call becomes enabled, since the first thing the *MouseClicked* process does, is receive that message. So, the *MouseClicked* process will be called and will receive the message from *OffsetEvent*. It will then instantiate (create) an *OffsetHandler* process. After that, it will send a request for a transaction to the *EditorManager*, which will respond with success (*em-transaction-started* message) or failure (*em-no-transaction* message). If it succeeded, it will check if there is a structure editor registered. If that is indeed the case, it will send a *handle-mouse-event* message, which will be routed to the appropriate place by the *OffsetHandler* process. The *MouseClicked* process will then synchronize the focus and inform the *EditorManager* that the transaction has ended.

It is not important why the scenario was implemented in this particular way. It is not even important that you understand how it works exactly. All we are interested in is how this scenario could look like in the new ToolBus. Figure 30 shows the same scenario as before, but now it is implemented in the new ToolBus.

In the current version, most of the messages have prefixes (like *em-* or *te-*). Now that we have namespaces, we can easily get rid of those prefixes by sending those messages in namespaces and instantiating some processes in namespaces.

Another difference is that in the new version the communication restriction applies. Both the *mouse-click-at-offset* message and the *set-cursor-at-offset* message are cut up into relay chains.

The new version is a direct translation of the current version, with some minor changes. However, in order to fully enjoy the benefits of the new features, the

[13] Version 2.0.1RC2 of the ASF+SDF Meta-Environment was used for this.

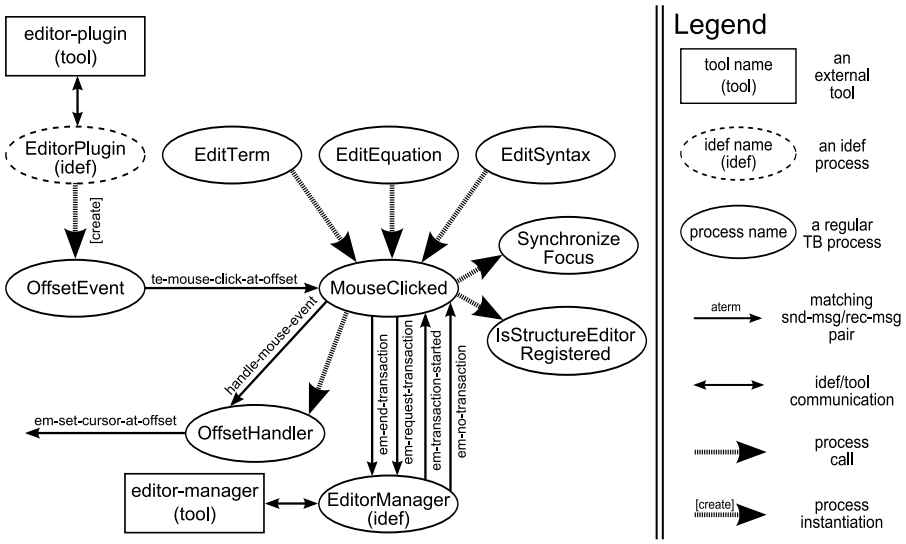


Figure 29: The MouseClicked scenario (current ToolBus)

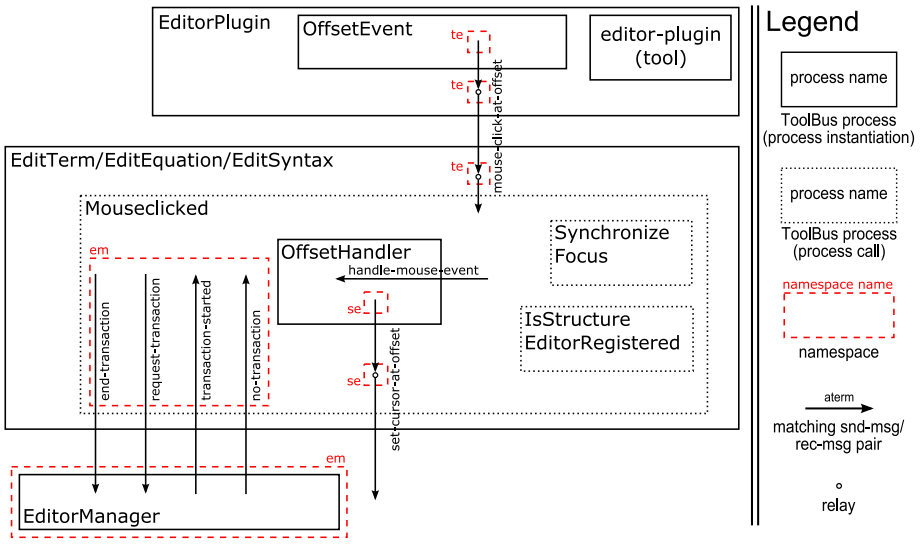


Figure 30: The MouseClicked scenario (new ToolBus)

ASF+SDF Meta-Environment will most likely have to undergo major restructuring. It for instance uses a lot of process calls. Process calls don't instantiate processes as independent entities, they sort of 'insert' the process definition of the called process into the calling process. Related to that is the use of process parameters as input and output of those 'methods' (invoked processes), which makes that messages are used less frequently. The new features are mostly targeted to systems that *instantiate* (as opposed to call) new processes and use *messages* (as opposed to process parameters) to communicate with them.

So, the question that remains is whether or not the new version is better than the old one. It is in the sense that name clashes are now solved by means of namespaces (for instance the *em* namespace). However, virtually nothing has changed structurally (thus it is not an improvement in that sense). Actually, it turned out to be impossible to find a group of only a few processes that could be extracted and used as a component. It turns out the processes in the ASF+SDF Meta-Environment are too tightly coupled and there is no structure present that can be used to turn it into a hierarchy. This is an indication that great benefit may come from restructuring it with the features introduced in this project.

8.2 The compiler system example revisited

Section 3.1 introduced the compiler system example. Figure 3 shows an overview of that system in the current ToolBus and Figure 31 shows what that system looks like in the new ToolBus.

In Figure 3 two 'structured process groups' are indicated. Obviously, in the current ToolBus there is no hierarchical structure, so they exist only in that figure. In the new ToolBus version, there *is* a hierarchical structure. We can clearly distinguish several 'structured process groups' (or components, or subsystems), like *CompilerSystem*, *JavaCompilerSystem* and *OptimizeCodeSystem*. The composition of the processes into components follows naturally and is easy to achieve. If we look at the *JavaCompilerSystem* component, we see that it has only three external messages. It is therefore easy to replace it by a different implementation, as long as that other implementation has the same interface (those three messages) as well as the same behavior. Also, all internal details are (automatically) hidden from the outside (mostly because of the communication restriction) as the interface consists of only three *exports* relays! Therefore it is very easy to reuse this component in another system.

It may be interesting to note that chaining is used only in two separate instances, while there are 16 instances of relays. This gives confidence that relays are useful and can indeed be used to optimize most uses of chaining.

There is also a difference between the two implementations of the compiler system example. In the current version, both the *JavaCompiler* process and the *CPPCompiler* process receive an *il-compile* message from process *Compiler* and both send a *compile-rslt* message to the *OptimizeCode* process. It would have been nice to have them send an *il-compile-rslt* message, but that was not possible, since such a message was already being sent by the *OptimizeCode* process to the *Compiler* process. This is an example of a name clash. In the

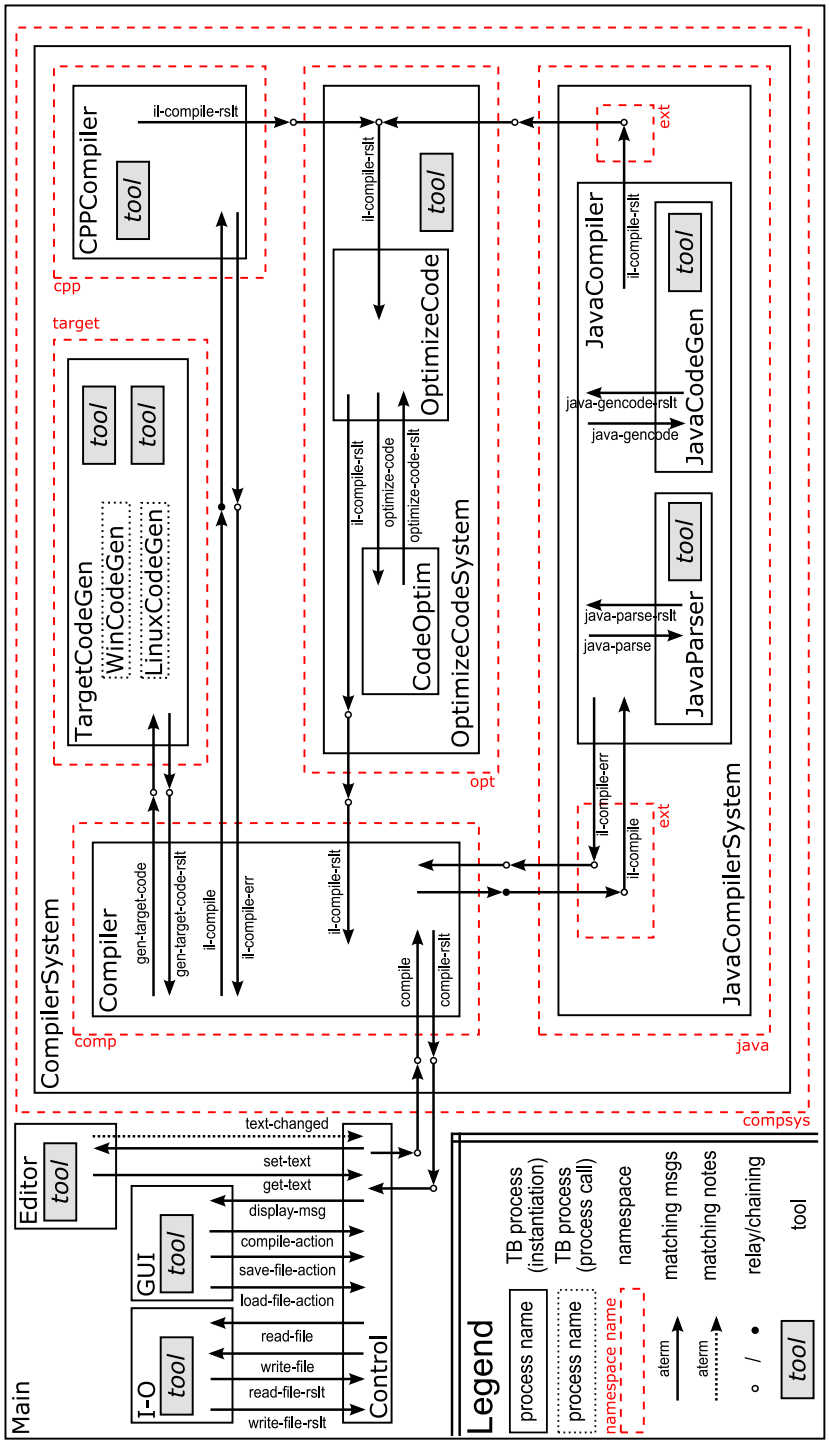


Figure 31: The compiler system example (new ToolBus)

new version we see that indeed *il-compile-rslt* messages are used in all those cases. Since namespaces are used, the messages can be differentiated!

It should be clear that the new version of the compiler system example is better than the old one. The name clash is solved with namespaces. Also, the structure of the components is now clearly visible. Finally, the components have limited external interfaces, as can be seen in Figure 32 (only the processes that have child processes are included). Note that the parts of the interface below the lines are included in the current definition of interface, but they shouldn't be (since, as explained in Section 7.2.2, those messages are used internally only).

```
[empty interface]
```

(Main)

```
exports(
 compile(<str>, <str>, <str>) in comp,
 compile-rslt(error(<str>)) in comp,
 compile-rslt(success(<str>)) in comp
)
---------------------------------------
rec-msg(comp/il-compile(<str>?, "Java"))
rec-msg(comp/il-compile(<str>?, "C++"))
snd-msg(java/ext/il-compile(<str>))
snd-msg(cpp/il-compile(<str>))
```

(CompilerSystem)

```
rec-msg(gen-target-code(<str>?, "Windows"))
rec-msg(gen-target-code(<str>?, "Linux"))
snd-msg(gen-target-code-rslt(<str>))
-------------------------------------------
```

(TargetCodeGen)

```
exports(
 compile-rslt(<str>),
 il-compile-rslt(<str>)
)
----------------------
```

(OptimizeCodeSystem)

```
exports(
 il-compile(<str>) in ext,
 il-compile-err(<str>) in ext,
 compile-rslt(<str>) in ext
)
------------------------------
```

(JavaCompilerSystem)

```
rec-msg(il-compile(<str>?))
snd-msg(il-compile-rslt(<str>))
snd-msg(il-compile-err(<str>))
snd-msg(il-compile-err(<str>))
-------------------------------------------
snd-msg(java-parse(<str>))
rec-msg(java-parse-rslt(error(<str>?)))
rec-msg(java-parse-rslt(success(<str>?)))
snd-msg(java-gencode(<str>))
rec-msg(java-gencode-rslt(error(<str>?)))
rec-msg(java-gencode-rslt(success(<str>?)))
```

(JavaCompiler)

Figure 32: Interfaces for new compiler system example

9 Implementation

This section discusses the implementation of the proposed solution.

9.1 Translation

One way of implementing the solution is to translate the new T scripts (with hierarchical processes, namespaces and relays) to semantically equivalent T scripts of the current ToolBus (the ones without namespaces, relays and hierarchical processes). See Appendix B for the details of the translation.

The fact that such a translation is possible proves that the changes and new features don't add any expressional power to the ToolBus, as was previously noted in Section 7.4.

The main benefit of this approach is that the current ToolBus system can be used (no changes to the ToolBus system itself are required). The biggest downside is that hierarchy and namespaces don't become actual concepts in the ToolBus and future extensions cannot build on them as they are translated away. Due to this downside, this translation has not (yet) been implemented.

9.2 Native support

Another way of implementing the solution is to natively support the new features in the ToolBus.

9.2.1 Benefit

The benefit of natively supporting the new features is that the ToolBus actually has them. Assume for instance, we want to implement dependability features, such as restarting of a subtree of the process hierarchy. If the ToolBus doesn't have a notion of process hierarchy (like when it is translated into a flat structure), it will be virtually impossible to implement those dependability features. So, by providing native support, future extensions can rely on for instance a hierarchical process structure and namespaces. Therefore, the decision was made to natively support the features and implement them into the ToolBus.

9.2.2 The ToolBusNG explained

Currently, a Java version of the ToolBus is being developed in the ToolBusNG project. This section very shortly explains how it works. However, all non-relevant details are omitted.

When the ToolBus is started, a *ToolBus* class is instantiated. It will create an instance of the *TScriptParser* class to parse the T scripts. The *TScriptParser*

class will instruct an external application to do the actual parsing. The external application uses a compiled SDF syntax definition of T scripts to do the parsing. After that, the resulting ATerm is used (by the *TScriptParser* class) to construct a state machine for each process using *NodeBuilder* classes. For each language concept there is *NodeBuilder* class. Finally, the *TScriptParser* class will instantiate the initial processes (the initial configuration) by creating instances of the *ProcessInstance* class.

When the parsing is completed, the *ToolBus* class will enter the *execute* method. That method will loop through all active process instances to see if they can make a step from the current state, which they can if their current action is enabled. If so, the action of the current state is executed and the next state is computed. Also, if the process has terminated, it will be removed from the list of active processes. The loop is repeated until non of the processes can change their state (non of the current actions of the processes is enabled). Then, all communication with the tools is processed. If there are still active processes left, then the *execute* method starts all over again, otherwise the ToolBus terminates.

All atoms (like *snd-msg*, *subscribe* and *create*) have corresponding classes (like *SndMsg*, *Subscribe* and *Create*) in the ToolBus that inherit from the abstract *Atom* class. This way it is easy to add new atoms. Also, each class has an *execute* method that will try to execute that atom and progress its corresponding process to the next state. It will return a boolean value whether the action could be executed (and the state was progressed) or not. For a *snd-msg* action, execution may fail when the action is not enabled or when none of the corresponding *rec-msg* actions is enabled. Note that when it does execute, not only the process that the *snd-msg* action belongs to progresses its state, as the process that the *rec-msg* action belongs to progresses its state as well.

The *ProcessInstance* class has several interesting methods. One of them is the *addPartnersToAllProcesses* method, which adds to each communication action of that process instance all the communication actions of other processes (called partners) that it may possibly communicate with. Also, it will add to all the partner communication actions (of the other processes) the corresponding communication actions of its own process instance. All communication related atom classes have methods for adding and removing partners. Related to the *addPartnersToAllProcesses* method is the *delPartnersFromAllProcesses* method, which doesn't add partners, but removes them.

9.2.3 Implementation details

The solution as presented in this thesis was implemented on a separate Subversion branch of the ToolBusNG implementation. The modularity of the ToolBusNG implementation made it rather easy to adapt it to the changes.

First, the hierarchical process structure was implemented. This is mainly just bookkeeping of the process relations. Each instance of the *ProcessInstance* class keeps track of its parent and its children. Also, the *ToolBus* class keeps track of the top level process. Furthermore, the `toolbus(...)` keywords are ignored during parsing and the top level process (*Main* by default) is instantiated in-

stead.

Then the communication restriction was implemented. This came down to restricting the partners that are added to each communication action (atom). To that end, the *addPartnersToAllProcesses* method was modified. After that, namespaces were up. The definition of T scripts (in SDF) had to be changed, as well as the parsing routines in the ToolBus (mainly the *NodeBuilder* classes). Bookkeeping was added for absolute and relative namespaces to all communication related classes that inherit from the *Atom* class. Also, the adding of partners was once again updated (this time in the *AddPartner* methods of the communication related atoms.

After namespaces, relays were implemented. Once again the SDF definition was updated along with the ToolBus parsing routines. Bookkeeping was added for relays (in the *ProcessInstance* classes) and the adding/removing of partners was completely overhauled.

After that, loop detection was added to the ToolBus, so that the ToolBus can warn the user about possibly unbounded recursions. Finally, dynamic (runtime) warnings were added for *snd-msg* atoms with more than one *rec-msg* partner.

10 Conclusions

In Section 5.2 the requirements for this project are listed. This section discusses to what extent the proposed solution satisfies those requirements. However, satisfying all the requirements is not enough to declare a project successful; the solution should also be useful in practice. A short discussion on that is included as well.

10.1 Requirements

Does the solution presented in Sections 6 satisfy all of the requirements? The relation to the requirements was already discussed in Section 7, but we will summarize the conclusions here.

It should be clear that the solution indeed introduces both hierarchy and (enforced) abstraction. This means that both requirements R1 and R2 are satisfied.

Interfaces are extracted from the definitions of the processes and are therefore implicit. They contain some internal details and are therefore far from optimal. This means that requirement R3 is satisfied to some extent, but definitely not completely.

The solution as it is makes it much easier to reuse a component of one system in another, thus satisfying requirement R4. However, the sub-optimal interfaces do complicate things a bit.

The semantics of the ToolBus have changed and at the moment there is no complete description of the new semantics. However, the formal semantics can be updated. This makes requirements R5 and R7 unsatisfied.

Old ToolBus systems (T scripts) can automatically be translated to semantically equivalent T scripts in the new format. Therefore it may be concluded that requirement R6 is satisfied.

There is an actual implementation of the solution as presented and it should therefore be possible to say something about the performance. However, the Java version of the ToolBus is still being developed. As such, there are no applications of reasonable size that use the Java version of the ToolBus. It would be nice to test the ASF+SDF Meta-Environment in the current ToolBus (the C version), the Java version (one that is more or less compatible with the C version) and the Java version with native support for hierarchical processes, the communication restriction, namespaces and relays. That way we could really test the performance. For now, all that can be said is that the implementations of the compiler system example in both the current ToolBus and the Java version of the ToolBus, with all the extensions as proposed in this project, seem to have equal performance. However, both implementations include stubs (in the form of ToolBus processes) for all of the tools. Whether requirement R8 is satisfied is thus still unclear.

Namespaces are introduced to solve the name clashes and they provide a lot of

freedom in doing so. This satisfies requirement R9.

The additional structure that is introduced to the ToolBus is indeed expected to make it easier to implement dependability features later on, thereby satisfying requirement R10.

So, requirement R3 is not completely satisfied. Therefore, it may be a good idea to look at completely different approaches to interfaces and see how they can be integrated into the ToolBus. Also, it is still unclear whether or not requirement R8 is satisfied. However, it is expected that performance is not a problem and in the future proof of this may become available. Finally, requirements R5 and R7 are not satisfied, but can be satisfied in the future.

10.2 Usefulness in practice

From the validation we can conclude that for some systems (like the compiler system example), using the new ToolBus system is easy and the additional structure comes natural. For other systems (like the ASF+SDF Meta-Environment), more work has to be done, as large parts of the system may have to be restructured. Depending on the kind of system, the benefits of the new features and amount of work that has to be done to fully benefit from them will have to be balanced.

For new systems it should be clear that they can be developed with the new features in mind. That way they can be used to their full potential. Especially in larger systems, their usefulness should be evident.

10.3 Final conclusion

Although not all of the requirements are completely satisfied, the solution as part of this project seems to be a step in the right direction. This becomes clear, for instance, when we look at the validation of the compiler system example. However, more experience with the use of the new concepts, in particular in the development of real-life systems, is needed to gain insight in the practical usefulness of the concepts. Time will tell if a solution similar to the one presented in this thesis is the way to go, or if a completely different solution is better. However, there is no doubt that this project will in some way be the first step towards more structure in the ToolBus.

11 Future work

This section will address some of the loose ends of the project. It also contains several suggestions for research that may be done in future projects.

11.1 Real life testing

It may be a good idea to get some actual experience with the changes in the new ToolBus by applying them to an existing (reasonably large) system, like the ASF+SDF Meta-Environment. By modifying it to make use of the hierarchical structure, namespaces and relays, it can be determined how easy (or hard) it is to adapt an existing system. Also, it could give more insight into the easy of reuse, replacement and evolution of subsystems, as well as the amount of chaining versus relays. Finally, it could allow for performance testing.

11.2 Compatibility

In Section 7.5 it was noted that it should be easy to translate old systems to equivalent ones in the new T script format. This translation is not yet implemented and it may be a good idea to do so. Also, integrating detection for old T scripts and allowing for automatic conversion could be implemented with minimal effort.

11.3 Dynamic namespaces

Currently, namespaces are static; you specify them at design time in the T scripts and they can't be changed at runtime. It would be interesting to have dynamic namespaces, where the namespace can be specified in the T script by just a (string) variable.

```
process P1 is
let Pid: int,
    Ns: str
in  rec-msg(Ns?) .
    create(Ns/P2, Pid?)
    /* omitted */
endlet
```

Figure 33: Example of a dynamic namespace

Figure 33 shows an example of a dynamic namespace. Process *P1* first receives a string value in variable *Ns*. Then it instantiates process *P2* in the namespace that it just received. Variable *Ns* could contain something like "x/y/z". Then process *P2* would be instantiated in namespace *x/y/z*.

There are some issues that need to be investigated. When sending and receiving messages (and notes) in dynamic namespaces, their partners cannot be determined at the time the process is instantiated and expensive checks have

to be performed each time a message is sent or received. This could decrease performance significantly. Also, it may be difficult for the parser to detect the difference between a static namespace and a variable name. A solution would be to put variable names in namespaces between some form of brackets or to prefix them with some dedicated character.

11.4 Process namespaces

Name clashes for messages are solved by means of namespaces. However, name clashes are also possible for process names. It would be interesting to see of the concept of namespaces could be extended to processes. Processes could be defined in namespaces, so that several processes with the same name could exist as long as they are defined in different namespaces. The definition of a process could then look something like this:

```
process x/y/z/P1 is ...
```

11.5 Protocols

Processes have interfaces. These interfaces show a list of possible communications that a process can engage in. However, processes also have *behavior*. Therefore, it may be nice to introduce *protocols* that define the (external) behavior of processes. One could look at protocols in a similar way as to interfaces in for instance Java; Java classes can be specified to implement a certain interface. Similarly, ToolBus processes could then be specified to implement a certain protocol, which would be defined separately. When replacing a subsystem X with another subsystem Y, subsystem Y should then not only have at least the interface of subsystem X, but it should also at least implement all the protocols that subsystem X implements. Note however that protocols would probably duplicate a large part of the definition of a process, which could lead to for instance maintenance problems.

11.6 Cycle detection

The current implementation includes a cycle detection algorithm that warns the user of possibly unbounded recursions in the system. Currently, it only warns the user about the first found cycle. The detection algorithm could be extended to (optionally) detect all cycles.

11.7 Interfaces

In Section 7.2.2 it was noted that the fact that interfaces include some internal details of the process is one of the biggest disadvantages of the solution. It could therefore be interesting to investigate if it is possible to somehow reduce, or even

eliminate, the internal details from interfaces. One such possible approach is (very shortly) explained below.

Currently, interfaces are inferred (or extracted) from the definitions of the processes; they are implicit in the process definitions. It would for instance be possible to add to each process a list of elements from the 'inferred interface' that are allowed to be external. This way, the added list would be the true external interface of the process. It would also be an *explicit* interface. The implementation of the ToolBus would then have to be adapted to make sure communication actions between a process and the environment only match if they are present in the 'external interface list' of the process. Such an implementation would most likely be reasonable easy to implement. This would solve the interface problems. However, T script programmers would have to add interfaces to all processes, which may be quite some work. Some practical tests could then be performed to see if the benefits outweigh the extra work. Also, interfaces would duplicate (possibly large) parts of process definitions.

If we take the above idea a step further, we could additionally introduce a concept of *abstract interfaces*, which are still lists of communication actions (and *exports* relays) as before. Instead of just indicating per process the list of communication actions that are external, we could also say its external interface contains one or more abstract interfaces. Processes would then sort of implement abstract interfaces. This would resemble the concept of interfaces in for instance Java and it could save the T script programmers quite some work. It would also make interfaces more reusable and it would allow for some verification, as it could be checked whether the process actually contains all the actions in the abstract interfaces.

11.8 Analysis of matching communication actions

Section 7.9 discussed the analysis of matching communication actions. There were two methods for performing such analysis, *dynamic* checking and *static* checking. The current implementation includes some limited dynamic checking, but much more is possible. The implementation contains methods that add partners to communication actions. Those methods take namespaces, relays and the communication restriction into account. Besides that, the ToolBus already parses T scripts. Therefore, it should be reasonable easy to use the existing functionality (with some modifications and additions) to do static checking with the ToolBus.

11.9 Semantics and formal foundation

Currently no document exists describing the formal semantics of the new version of the ToolBus, as was stated in Section 7.4. Therefore, the formal semantics of the ToolBus should be updated to include the new features. That way the formal foundation of the ToolBus can be restored. Since the formal foundation is one of the biggest selling-points of the ToolBus, this should be done sooner rather than later.

11.10 Dependability

This project is partly about making it easier to implement dependability features at a later stage. In Section 5.2 it was noted that structural isolation and physical isolation are prerequisites for implementing such dependability features. It was also noted that this project would only be concerned with making processes structurally isolated.

Physical isolation can be achieved in several ways, for instance by putting groups of ToolBus processes in different threads or even in different ToolBus instances. The common goal is to make sure that if the processes in one 'group' (or *execution space*) crash or deadlock, that won't (directly) influence the processes running in another space. Also, each space should have its own resources.

Obviously, the designer of a system should have full control over which processes will be instantiated in what space. Since subsystems usually have coherent behavior, it may be a good idea to put all processes of a subsystem together in a space.

One of the big open questions is how to indicate in which space a process should be instantiated. We could adopt a new keyword, say `createnew(...)` that instantiates the process in a new unnamed space. The existing `create(...)` keyword would then instantiate processes in its own space (in the space of the instantiating process). This way, entire subtrees are automatically instantiated in a new space. However, that would mean that a process can't instantiate two processes in the same new space. The developer wouldn't have *full* control.

It would be possible to extend the instantiation keywords with a third parameter[14] that indicates the name or identifier of the space that the process should be instantiated in. It would then be possible to add a keyword for explicit space creation or a space could just be created the first time a process is instantiated in it.

In general, these are the questions that need to be answered:

- Do we want creation of a space and instantiation of a process in it in the same action (keyword) or do we want separate keywords for that?
- Do we want named execution spaces or not?
- If execution spaces have names or identifiers, are they defined explicitly, or used implicitly?
- If execution spaces have names or identifiers, are they local of global?
- Do we want to use existing keywords as much as possible or do we introduce new ones?

When we have decided how spaces are created and how processes can be instantiated in them, one important question remains: how do we implement the

[14]The first parameter is the name of the process to be instantiated, together with its arguments. The second one is the Process ID that is returned.

interaction (communication, negotiation, etc.) between the different spaces? In order words: how is it determined what actions can and will communicate?

There are a lot of questions that need to be answered before physical isolation can be implemented. These questions should be much easier to answer once the exact (requirements for the) dependability features are known and perhaps partly designed. The conclusion is that physical isolation can best be designed and implemented together with the dependability features.

A SDF syntax of T scripts

This appendix contains the full SDF syntax of T scripts with the extensions and changes as described in Section 6. Figure 34 contains the SDF import graph.

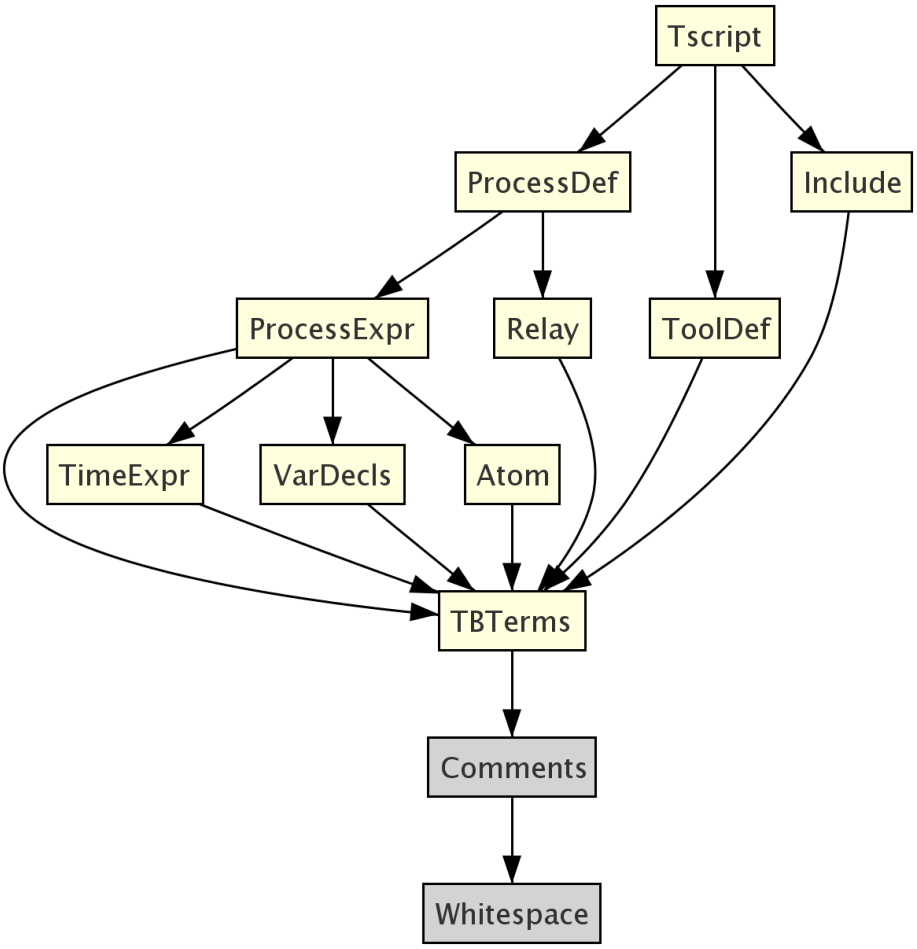


Figure 34: SDF import graph

Tscript.sdf:

```
module Tscript
imports ProcessDef ToolDef Include

exports
  sorts Tscript ToolBusConfig Ifndef Ifdef Decl

  context-free start-symbols Tscript

  context-free syntax

    "toolbus" "(" {ProcessCall ","}+ ")"      -> ToolBusConfig
    ( ProcessDef | ToolDef | ToolBusConfig | Include | Define | Ifdef | Ifndef )
                                              -> Decl
    "#ifdef" Vname Decl*  "#endif"            -> Ifdef {cons("ttt-Ifdef")}
```

```
    "#ifndef" Vname Decl* "#endif"            -> Ifndef {cons("ttt-Ifndef")}
    Decl*                                     -> Tscript {cons("ttt-Tscript")}
```

ProcessDef.sdf:

```
module ProcessDef
imports ProcessExpr Relay

exports
  sorts ProcessDef ProcessDefs

  context-free syntax

    "process" ProcessName "is" Relays? ProcessExpr
                -> ProcessDef  {cons("ttt-ProcessDefinition0")}

    "process" ProcessName "(" {VarDecl ","}* ")" "is" Relays? ProcessExpr
                -> ProcessDef  {cons("ttt-ProcessDefinition")}

    ProcessDef*   -> ProcessDefs
```

ToolDef.sdf:

```
module ToolDef
imports TBTerms

exports
  sorts ToolDef Host Kind Command

  context-free syntax

    "tool" Id  "is" "{" Host? Kind? Command? "}" -> ToolDef {cons("ttt-ToolDef")}
    "kind" "=" String                            -> Kind    {cons("ttt-kind")}
    "host" "=" String                            -> Host    {cons("ttt-host")}
    "command" "=" String                         -> Command {cons("ttt-command")}
```

Include.sdf:

```
module Include
imports TBTerms

exports
  sorts Include Define

  context-free syntax

    "#include" FileName     -> Include {cons("ttt-Include")}
    "#define" Vname         -> Define  {cons("ttt-Define0")}
    "#define" Vname TBTerm  -> Define  {cons("ttt-Define1")}
```

ProcessExpr.sdf:

```
module ProcessExpr
imports Atom VarDecls TimeExpr TBTerms

exports
  sorts ProcessExpr ProcessName ProcessCall Invocation

  lexical syntax

    [A-Z] [a-zA-Z0-9\-]*                  -> ProcessName {cons("ttt-id")}

  context-free syntax
```

```
  ProcessName                              -> Invocation {cons("ttt-apply")}
  ProcessName "(" {TBTerm ","}* ")"        -> Invocation {cons("ttt-apply")}

  Namespace"/"Invocation                   -> ProcInvoc {cons("ttt-procinvoc")}
  Invocation                               -> ProcInvoc {cons("ttt-procinvoc")}

  Atom                                     -> ProcessExpr
  Atom TimeExpr                            -> ProcessExpr {cons("ttt-TimeExpr")}
  "create" "(" ProcInvoc  "," GenVar ")"   -> ProcessExpr {cons("ttt-Create")}
  Invocation                               -> ProcessCall {cons("ttt-ProcessCall")}
  ProcessCall                              -> ProcessExpr

  ProcessExpr "." ProcessExpr      -> ProcessExpr {right, cons("ttt-Sequence")}
  ProcessExpr "+" ProcessExpr      -> ProcessExpr {left, cons("ttt-Alternative")}
  ProcessExpr "*" ProcessExpr      -> ProcessExpr {left, cons("ttt-Iteration")}
  ProcessExpr "||" ProcessExpr     -> ProcessExpr {left, cons("ttt-Merge")}
  ProcessExpr ">>" ProcessExpr     -> ProcessExpr {right, cons("ttt-Disrupt")}
  "(" ProcessExpr ")"              -> ProcessExpr {bracket}
  "let" VarDecls "in" ProcessExpr "endlet"
                                   -> ProcessExpr {cons("ttt-LetDefinition")}
  "if" TBTerm "then" ProcessExpr "fi"
                                   -> ProcessExpr {cons("ttt-IfThen")}
  "if" TBTerm "then" ProcessExpr "else" ProcessExpr "fi"
                                   -> ProcessExpr {cons("ttt-IfElse")}

context-free priorities

  ProcessExpr "*" ProcessExpr  -> ProcessExpr {left, cons("ttt-Iteration")} >
  ProcessExpr "." ProcessExpr  -> ProcessExpr {right, cons("ttt-Sequence")}  >
  ProcessExpr "+" ProcessExpr  -> ProcessExpr {left, cons("ttt-Alternative")}>
  ProcessExpr "||" ProcessExpr -> ProcessExpr {left, cons("ttt-Merge")} >
  ProcessExpr ">>" ProcessExpr -> ProcessExpr {right, cons("ttt-Disrupt")}
```

Relay.sdf:

```
module Relay
imports TBTerms

exports
  sorts Relays

  context-free start-symbols

       Relays

  context-free syntax

    ExportsBlock                   -> Relays {cons("ttt-Relays")}
    ConnectsBlock                  -> Relays {cons("ttt-Relays")}

    ExportsBlock ConnectsBlock     -> Relays {cons("ttt-Relays")}
    ConnectsBlock ExportsBlock     -> Relays {cons("ttt-Relays")}

    "exports" "(" RelayItems ")"   -> ExportsBlock {cons("ttt-ExportsBlock")}
    "connects" "(" RelayItems ")"  -> ConnectsBlock {cons("ttt-ConnectsBlock")}

    { RelayItem "," }+             -> RelayItems

    TBMsg                          -> RelayItem {cons("ttt-RelayItem")}
    TBMsg "in" Namespace           -> RelayItem {cons("ttt-RelayItem")}
    TBMsg "in" EmptyRelayNamespace -> RelayItem {cons("ttt-RelayItem")}

    "/"                            -> EmptyRelayNamespace {cons("ttt-EmptyRelayNS")}
```

Atom.sdf:

```
module Atom
imports TBTerms
```

```
exports
  sorts Atom

  context-free syntax

    %% communication atoms
    "snd-msg" "(" TBMsg ")"           -> Atom {cons("ttt-SndMsg")}
    "rec-msg" "(" TBMsg ")"           -> Atom {cons("ttt-RecMsg")}

    %% note atoms
    "subscribe" "(" TBMsg ")"         -> Atom {cons("ttt-Subscribe")}
    "unsubscribe" "(" TBMsg ")"       -> Atom {cons("ttt-UnSubscribe")}
    "snd-note" "(" TBMsg ")"          -> Atom {cons("ttt-SndNote")}
    "rec-note" "(" TBMsg ")"          -> Atom {cons("ttt-RecNote")}
    "no-note" "(" TBMsg ")"           -> Atom {cons("ttt-NoNote")}

    %% tool atoms
    "execute" "(" TBTerm "," TBTerm ")"          -> Atom {cons("ttt-Execute")}
    "rec-connect" "(" TBTerm ")"                 -> Atom {cons("ttt-RecConnect")}
    "rec-disconnect" "(" TBTerm ")"              -> Atom {cons("ttt-RecDisConnect")}
    "snd-terminate" "(" TBTerm "," TBTerm ")"    -> Atom {cons("ttt-SndTerminate")}

    "rec-event" "(" TBTermList ")"               -> Atom {cons("ttt-Event")}
    "snd-ack-event" "(" TBTerm "," TBTerm ")"    -> Atom {cons("ttt-AckEvent")}
    "snd-eval" "(" TBTerm "," TBTerm ")"         -> Atom {cons("ttt-Eval")}
    "rec-value" "(" TBTerm "," TBTerm ")"        -> Atom {cons("ttt-RecVal")}
    "snd-do" "(" TBTerm "," TBTerm ")"           -> Atom {cons("ttt-Do")}

    %% delta and tau
    "tau"                             -> Atom {cons("ttt-Tau")}
    "delta"                           -> Atom {cons("ttt-Delta")}

    %% read and print
    "printf" "(" TBTermList ")"       -> Atom {cons("ttt-Print")}
    "read" "(" TBTermList ")"         -> Atom {cons("ttt-Read")}

    %% shutdown
    "shutdown" "(" TBTerm ")"         -> Atom {cons("ttt-ShutDown")}

    %% Assign
    Var ":=" TBTerm                   -> Atom {cons("ttt-Assign")}
```

VarDecls.sdf:

```
module VarDecls
imports TBTerms

exports
  sorts VarDecl VarDecls

  context-free syntax

    Var ":" TBTerm      -> VarDecl  {cons("ttt-vardecl")}
    Var ":" TBTerm "?"  -> VarDecl  {cons("ttt-resvardecl")}
    {VarDecl ","}*      -> VarDecls
```

TimeExpr.sdf:

```
module TimeExpr
imports TBTerms

exports
  sorts TimeExpr

  context-free syntax

    "delay" "(" TBTerm ")"     -> TimeExpr {cons("ttt-delay")}
    "timeout" "(" TBTerm ")"   -> TimeExpr {cons("ttt-timeout")}
```

TBTerms.sdf:

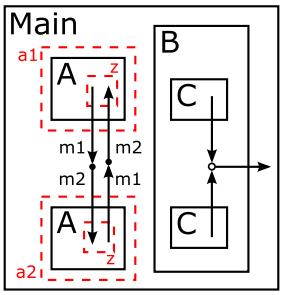
```
module TBTerms
imports basic/Comments

exports
  sorts NatCon Nat Int Real Id Vname TBTerm TBTermList Var GenVar
  sorts StrCon String L-Char EscChar FileName

  lexical syntax

    [0-9]+                          -> NatCon
    [a-z] [a-zA-Z0-9\-\_]*          -> Id
    "\\" ~[]                        -> EscChar {avoid}
    ~[\0-\31\"\\] \/ [\t\n]         -> L-Char
    EscChar                         -> L-Char
    "\"" L-Char* "\""               -> StrCon
    "<" L-Char* ">"                 -> FileName
    [A-Z\_] [a-zA-Z0-9\_]*          -> Vname

    [\*]                            -> Asterisk
    "/*" ( ~[\*] | Asterisk )* "*/" -> LAYOUT

  lexical restrictions

    NatCon -/- [0-9]
    Id -/- [a-zA-Z0-9\-]
    Vname -/- [a-zA-Z0-9\-]
    Asterisk -/- [\/]

  context-free syntax

    NatCon                          -> Nat    {cons("ttt-natcon")}
    Int "." NatCon                  -> Real   {cons("ttt-realcon")}
    "(" Nat ")"                     -> Nat    {bracket}
    Nat                             -> Int
    "+" Nat                         -> Int    {cons("ttt-posint")}
    "-" Nat                         -> Int    {cons("ttt-negint")}
    "(" Int ")"                     -> Int    {bracket}
    StrCon                          -> String {cons("ttt-strcon")}

    Vname                           -> Var
    Var                             -> GenVar  {cons("ttt-var")}
    Var "?"                         -> GenVar  {cons("ttt-resvar")}

    Int                             -> TBTerm
    Real                            -> TBTerm
    String                          -> TBTerm
    GenVar                          -> TBTerm
    "<" TBTerm ">"                  -> TBTerm  {cons("ttt-placeholder")}
    Id                              -> TBTerm
    Id "(" TBTermList ")"           -> TBTerm  {cons("ttt-apply")}
    "[" TBTermList "]"              -> TBTerm
    {TBTerm ","}*                   -> TBTermList

    { Id "/"}+                      -> Namespace

    Namespace"/"TBTerm              -> TBMsg   {cons("ttt-msg")}
    TBTerm                          -> TBMsg   {cons("ttt-msg")}
```

B T script translation

This appendix contains all details on the translation of new T scripts to semantically equivalent T scripts in the format of the current ToolBus.

B.1 Example

The translation will be demonstrated by means of an example. Figure 35 shows a system with namespaces, relays and hierarchical processes, including the T script files that go with it. We start the translation with an empty output file, say *translated.tb*.



(System overview)

```
#include <abc.tb>

process Main is
  let Pid: int
  in create(a1/A, Pid?) .
     create(a2/A, Pid?) .
     create(B, Pid?) .
     snd-msg(a1/z/m2) .
     ( rec-msg(a1/z/m1) .
       snd-msg(a2/z/m2)
     +
       rec-msg(a2/z/m1) .
       snd-msg(a1/z/m2)
     +
       rec-msg(m3)
     ) * delta
  endlet
```

(main.tb)

```
process A is
  ( rec-msg(z/m2) .
    snd-msg(z/m1)
  ) * delta

process B is
  exports(m3)
  let Pid: int
  in  create(C, Pid?) .
      create(C, Pid?)
  endlet

process C is
  ( snd-msg(m3)
      delay(sec(10))
  ) * delta
```

(abc.tb)

Figure 35: Example of a new system

B.2 The top of the hierarchy

In the new ToolBus, the process at the top of the hierarchy (in our case process *Main*) is automatically instantiated. In order to get the same result in the translated version, we need to include the following line in the output file:

```
toolbus(Main)
```

B.3 Process names

Figure 36 shows the process hierarchy (process instantiation tree) of our example system. We see that some processes are instantiated multiple times. In the translated version, we can't have multiple processes with the same name. So, we have to do a translation. First, we prefix all process instantiations with their absolute namespace. We replace all '/' characters with '-' characters. Then, we traverse the tree. Each time we encounter a process instantiation, we add

a number to it. We add a '1' to the first process, a '2' to the second process, and so on... We make sure that all the number we add are of equal length. That is, if we have 105 processes, we add '001' to the first process. That way it's three characters long, just like '105'. The result of this renaming is also depicted in Figure 36. We will refer to the number that was added to a process as the *Process ID*.

(Original tree) (Translated tree)

Figure 36: Process instantiation trees

After the renaming, we add a definition for each process in the tree to the output file. For our example, this means we have to add six process definitions. We change the process names everywhere to the renamed ones.

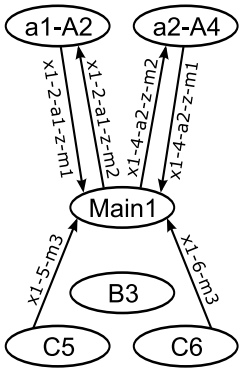
B.4 Communications

Namespaces are not supported by the current ToolBus. Therefore we will have to do a translation for them as well. First, we remove the relative namespaces. Then, similarly as for processes, we prefix all messages (and notes) with their absolute namespace.

In the new ToolBus, the communication restriction applies, in the current ToolBus it doesn't. Also, the new ToolBus supports relays, while the current ToolBus doesn't. Both have to do with which messages may directly communicate.

To translate, we first remove all relays (`exports(...)` and `connects(...)` keywords) from the output file. Then we go over every communication action in the file. For each action, we check with which other actions it may directly communicate in the new system (taking the communication restriction, namespaces and relays into account). Then we prefix the matching communication actions with an 'x' character and the Process IDs of the processes the two actions belong to (in ascending order), with a '-' character after each Process ID. If a single communication action (the source) may directly communicate with more than one other communication action (multiple targets), we create an alternative composition consisting of multiple times the source, but with different prefixes for the different targets.

The result of the entire translation is depicted in Figure 37 (process creation arrows are omitted). This concludes the translation process, which can be fully automated!



(Translated system)

```
process Main1 is
  let Pid: int
  in create(a1-A2, Pid?) .
     create(a2-A4, Pid?) .
     create(B3, Pid?) .
     snd-msg(x1-2-a1-z-m2) .
     ( rec-msg(x1-2-a1-z-m1) .
       snd-msg(x1-4-a2-z-m2)
     +
       rec-msg(x1-4-a2-z-m1) .
       snd-msg(x1-2-a1-z-m2)
     +
       (
         rec-msg(x1-5-m3)
       +
         rec-msg(x1-6-m3)
       )
     ) * delta
  endlet

process B3 is
  let Pid: int
  in  create(C5, Pid?) .
      create(C6, Pid?)
  endlet
```

(translated.tb)

```
process a1-A2 is
  ( rec-msg(x1-2-a1-z-m2) .
    snd-msg(x1-2-a1-z-m1)
  ) * delta

process a2-A4 is
  ( rec-msg(x1-4-a2-z-m2) .
    snd-msg(x1-4-a2-z-m1)
  ) * delta

process C5 is
  ( snd-msg(x1-5-m3)
      delay(sec(10))
  ) * delta

process C6 is
  ( snd-msg(x1-6-m3)
      delay(sec(10))
  ) * delta

toolbus(Main1)
```

Figure 37: Example of a translated system

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